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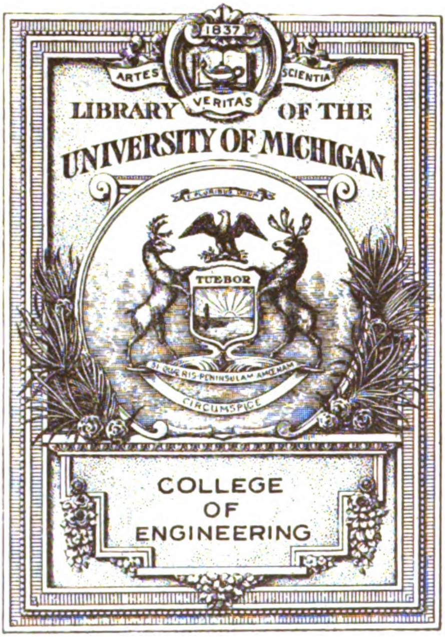

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MAKERS OF SCIENCE

Electricity & Magnetism

by

orothy abel
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With an Introduction

by

CHARLES SINGER

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PREFACE

In this little volume I have attempted to describe the main developments of electrical science as far as the end of the nineteenth century. With the approach to modern times more and more condensation has been imperative. The achievements of the present century are thus of necessity indicated merely in outline. Their treatment would require long excursions into the intricacies of modern physics and would thus lead us outside the scope of the present volume.

The book is addressed to the young student and to the general reader interested in the progress of science. I have therefore endeavoured, without mathematical elaborations, to indicate the methods by which the great experimenters have worked. Such calculus as has been employed is printed in small type and may be omitted without the sense of the passage being lost. The biographical notes will give a natural explanation of the eponymic terms with which electrical science abounds. I have given references to the more accessible literature of the subject as an aid to the student who may wish to follow up any particular line of development in greater detail.

My thanks are due to my friend, Dr. Ivor Hart, for suggestions and help with the proofs, and to my father for help with the illustrations. Particularly my thanks are due to Dr. Charles Singer for his criticism, generous help and advice throughout the whole of my labours.

D. M. TURNER.

University College,
October, 1926.

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CONTENTS

PAGE

INTRODUCTION - - - - - - - - - - - ix

I. EARLY SPECULATIONS - - - - - - - 1

Antiquity, 1 ; The Middle Ages, 2 ; William Gilbert, 5 ; Seventeenth Century after Gilbert, 12.

II. ELECTROSTATICS IN THE EIGHTEENTH CENTURY - - - - - - - - - 16

The Doctrine of Imponderables in the Eighteenth Century, 16 ; Conceptions of the Nature of Electricity in the Early Eighteenth Century, 17 ; Some Early Experiments on Static Electricity, 19 ; The First Mention of Different Electrifications, 21 ; The Storing of Electricity. Invention of the Leyden Jar, 22 ; Benjamin Franklin, 24 ; Priestley and the Law of Inverse Squares, 27 ; Some Early Electrical Machines, 28 ; The Work of Cavendish, 31 ; Later Experiments in Continuation of the Work of Cavendish, 36.

III. THE ELECTRIC CURRENT - - - - - - 40

Galvani, 40 ; Volta, 43 ; Investigations in England, 44 ; Humphry Davy, 46 ; Beginnings of the Ionic Theory, 51.

IV. ELECTRO-MAGNETISM - - - - - - - 53

Study of Magnetism in the Eighteenth Century, 53 ; Oersted's Discovery, 54 ; Immediate Results of Oersted's Experiments. Work of Arago, Biot, and Savart, 57 ; Ampère, 60 ; The Researches of Ampère, 63 ; Galvanometers, 73 ; Further Developments in the Study of Electricity, 75 ; The Work of Ohm, 76.

V. THE DISCOVERY OF ELECTRO-MAGNETIC INDUCTION - - - - - - - - - 81

The Early Life of Faraday, 81 ; Faraday as Davy's Assistant, 82 ; Electro-magnetic Rotations, 85 ; The Middle Period of Faraday's Career, 88 ; Electro-magnetic Induction, 91 ; Faraday's Conception of Lines of Force, 96 ; Later Work of Faraday, 100.

PAGE

VI. ELECTRICAL MEASUREMENTS AND SOME PRACTICAL APPLICATION - - - - - 103

Applications of Faraday's Discoveries, 103; Early Attempts to Measure Electrical Resistance, 107; Improvements in Electrical Apparatus, 110; William Thomson—Lord Kelvin, 111; Units—Fundamental and Derived, 114; Measurement of Electrical Quantities in Absolute Units, 115; Practical Units, 120.

VII. DEVELOPMENT OF ELECTRICAL THEORY - 122

Before Maxwell, 122; Clerk Maxwell, 125; Maxwell's Conception of the Electro-magnetic Field, 130; The Electro-magnetic Theory of Light, 133; The Successors of Maxwell, 136.

VIII. ELECTROLYSIS - - - - - - - - - 141

Faraday's Laws, 141; Electrolytic Dissociation, 144; Measurement of the Velocities of Ions, 147; The Ionic Theory of Arrhenius, 149; Theory of the Voltaic Cell, 150.

IX. THE CONDUCTION OF ELECTRICITY THROUGH GASES - - - - - - - - 153

Closing Years of the Nineteenth Century, 153; Early Experiments on the Discharge through Gases, 153; Progress with Improved Apparatus, 156; First Evidence as to the Atomic Nature of Electricity, 159; Ionisation of Gases, 161; Commencement of the Modern Period of Physical Research, 163.

X. ELECTRICAL CONSTITUTION OF MATTER. - 173

Radioactivity, 173; Electrons and Pistons, 175; Electricity and Matter, 177.

INDEX - - - - - - - - - - 180

LIST OF ILLUSTRATIONS

PAGE
1. Page from *Epistola de Magnete* of Peregrinus - - - - - 3
2. Leonardo's floating magnet - - - - - - - - 4
3. Compass card of Cecco d'Ascoli (1521) - - - - - - 5
4. One of Gilbert's Lodestones - - - - - - - - 6
5. Gilbert's Versorium - - - - - - - - - 7
6. One of Gilbert's irregular terrellae with versoria - - - 8
7. One of Gilbert's terrellae showing the dip of the magnet in various latitudes - - - - - - - - 9
8. Diagram showing dip - - - - - - - - 9
9. Gilbert's dip needle - - - - - - - - - 10
WILLIAM GILBERT, - - - - - - - - - 13
ROBERT BOYLE - - - - - - - - - 15
10. The first Leyden jar - - - - - - - - - 22
11. Watson's Leyden jar - - - - - - - - - 23
BENJAMIN FRANKLIN - - - - - - - - - 25
12. Hauksbee's Electrical Machine - - - - - - - 29
13. Watson's Electrical Machine - - - - - - - - 29
14. Priestley's Electrical Machine - - - - - - - 30
15. Hollow hemispheres used by Cavendish - - - - - 35
16. Illustrating the force at a point within a hollow charged conductor - - - - - - - - - - 35
17. Torsion balance - - - - - - - - - - 37
18. Galvani's experiments - - - - - - - - - 41
19. From an early work on Galvanism showing the supposed production of animal electricity - - - - - - 42
20. Volta's Crown of cups - - - - - - - - - 43
HUMPHRY DAVY - - - - - - - - - - 47
21. Oersted's Experiment - - - - - - - - - 56
22. Arago's rotations - - - - - - - - - 58
23. Simple electro-magnet - - - - - - - - - 59
24. Horse-shoe electro-magnet - - - - - - - - 59
ANDRÉ MARIE AMPÈRE, - - - - - - - - - 61
25. Ampère's Apparatus I - - - - - - - - - 64
Simplified diagram from *Annales de Chimie*, 1820, 15, Pl. 1
26. Ampère's second experiment - - - - - - - - 64
27. Apparatus showing action of helical currents - - - - - 65
28. Ampère's astatic balance - - - - - - - - 67
29. Ampère's experiment showing the effect of currents in opposite directions on the astatic balance - - - - - 67

List of Illustrations

PAGE

30. Ampère's apparatus with a conductor capable of moving only in the direction of its length - - - - - - - - 68
31. Ampère's apparatus for testing the simultaneous effect of two circuits on the astatic balance - - - - - - - - 69
32. Force at a point on the axis of a circular coil - - - - - 70
33. Molecular currents in a magnetic shell - - - - - - - 72
34. Ampère's swimmer - - - - - - - - - - - 72
35. Schweigger's multiplier - - - - - - - - - - 74
36. Arrangement of two magnets to form an astatic pair - - 75
MICHAEL FARADAY - - - - - - - - - - 83
37. From *Exp. Res.*, Vol. 2, Plate 4, Fig. 1 - - - - - - 87
38. From *Exp. Res.*, Vol. 2, Plate 4, Fig. 5 - - - - - - 87
39. Faraday's ring - - - - - - - - - - - 93
40. From *Exp. Res.*, Series I, Plate 1, Fig. 2 - - - - - 93
41. From *Exp. Res.*, Series I, Plate 1, Fig. 4 - - - - - 94
42. Lines of force due to a current in a straight conductor - - 98
43. Resultant field due to two currents in the same direction - 99
44. Resultant field due to two currents in opposite directions - 99
45. Simplest form of dynamo or motor - - - - - - 103
46. Induction coil - - - - - - - - - - - 105
47. The Magneto - - - - - - - - - - - - 106
48. The Transformer - - - - - - - - - - - 106
49. Simplest form of telephone transmitter - - - - - - 107
50. Christie's resistance balance - - - - - - - - 109
51. Wheatstone's Bridge with uniform wire and sliding contact - 110
LORD KELVIN - - - - - - - - - - - - 113
52. Quadrant Electrometer - - - - - - - - - - 117
53. Kirchhoff's circuit - - - - - - - - - - - 119
54. Illustrating Weber's molecular theory - - - - - - 124
JAMES CLERK MAXWELL - - - - - - - - - - 127
55. Illustrating Maxwell's Vortices - - - - - - - - 132
56. One form of oscillator and detector used by Hertz - - - 138
57. Simple circuit for the transmission of electro-magnetic waves - 139
58. Illustrating Faraday's second law of electrolysis - - - 142
59. Daniell's cell - - - - - - - - - - - - 146
60. Modified form of Wheatstone's Bridge used by Kohlrausch - 148
61. Tube used in Watson's experiments - - - - - - - 154
62. Discharge tube showing the positions of the dark spaces and striations - - - - - - - - - - - - 158
63. Type of tube with which Röntgen discovered X-rays - - 166
64. J. J. Thomson's modification of Perrin's tube - - - - 167
65. Discharge tube used in J. J. Thomson's experiments - - 168

INTRODUCTION

§ 1. *The Defect in Scientific Education*

It is, in my opinion, a very serious defect in our educational system that the Sciences are taught as though the men of science of our day were the repositories of a system of absolute knowledge capable, doubtless, of extension, but of correction only in minor details. This standpoint, it is needless to say, is not that occupied by any philosophical man of science. But men of science are rare, philosophers are rarer, while philosophers who are also men of science are rarer yet. It is too much to hope that, in this imperfect world, every teacher will have a taste or a training for both these disciplines. It is not, however, too much to hope that schemes of education should be so thought out that Science should not be taught in a manner that runs counter to the best scientific attitude of the day.

Now it is clear that the body of scientific knowledge that is in our possession is the product of many generations of growth along particular lines. Had the lines of growth been different, had the social, intellectual, political, religious, psychological environment of those generations been other than in fact they were, then the resulting body of knowledge would have been different from what it now is. In essence the History of Science consists of a series of acts of judgment by the men of the past on the record of observational findings as presented to them. From this series of findings and the judgments upon them has resulted the body of scientific knowledge which is in our hands. That body of knowledge is a living and growing thing, the result of living and organic causes. We cannot comprehend the living organism unless we know its inheritance and upbringing, we cannot understand the child unless we are acquainted with its parents and its home, we cannot form a clear picture of the government of our country unless we know its political history, and we cannot attain to an educationally valuable knowledge of Science unless we know also how that body of thought came to be what in fact it is. We must understand the judgments on which it has come to be based. Long before the days of Comte, Goethe assured us that the History of Science was Science itself.

§2. *The Ideal Remedy*

What is the remedy for this gap in our educational system? In my opinion the real remedy is a very drastic one, so drastic that I do not contemplate its early introduction as in any way a matter of current practical educational policy. The proper and logical remedy is to recast the 'humane' side of our education. What we really want is a proper training in the history of those things that make life worth living, so that the pupil may obtain some clear vision of why, in fact, life *is* worth living. The things that make life worth living may be summed up in the word *Civilisation*. There have been, and there are, different civilisations that have made life worth living in different ways, and that have therefore demanded different educational systems. Fortunately, we are effectively concerned with but one Civilisation, but the history of that should form the central topic of our school training.

The old so-called 'Classical Education' was historically an attempt to introduce the History of Civilisation as the basis of education. The humanists of the fifteenth and sixteenth centuries who gave the Classics their place as the standard school subject doubtless erred in the weight they gave to literary excellence. Moreover, their historical perspective was gravely warped. Yet their scheme had prolonged success. This was due, as I believe, to the fact that in its day it represented an attempt to base education on a presentation of the most important elements in Civilisation. It has failed because its vision was partial and biased, nor has it proved itself capable of ready adaptation to new conditions.

In the ideal development the History of Civilisation should cover all sides of man's life, and special care should be taken that fanatics and cranks and one-sided persons should not be allowed to bias education in the direction of their own particular interests. The history books that are available for school teaching are, in fact, overwhelmingly biased towards politics. What is called a ' History of England ' is, in nine cases out of ten, a ' History of English Politics.' But man doth not live by Politics alone—or at least few of us so live! Nor do we even live by Politics leavened by Economics. ' Man doth not live by bread only, but by every word that proceedeth out of the mouth of the Lord doth man live.'

I am far from desiring that the ' History of Science ' should take the place of the ' History of Politics,' but it is a fact that Science has, during the last three hundred years, played a great part in the shaping of men's thoughts and lives. The scientific idea, the conception that order reigns in nature and that order can be traced and demonstrated wherever and whenever men take the pains so to do, has utterly transformed our outlook and is beginning to transform our inlook. It long ago changed men's relation to the world around them. During the last century and since the rise of the social and anthropological sciences it has been altering man's relation to man. In the last generation, with the rise of Psychology into the position of one of the positive sciences, it has begun to change man's way of regarding himself. The ' History of Science ' should, therefore, find a due but not an undue share in our ideal school ' History of Civilisation.' Training in such a subject would, in my opinion, have a no less humanising influence than the study of such subjects as language, history, literature or science itself, studies which would naturally grow out of it. The proper place for the History of Science is as an integral part of the History of Civilisation.

This is my own private vision, however, which I have no great hope or expectation of seeing widely shared, still less adopted by others. But what I would urge is the regular adoption into the school curriculum of an elementary instruction in the *History of*

Civilisation. It can be done. There are several books on the subject available.

§ 3. *Some Practical Suggestions*

From what I have said it will be gathered that I lay more emphasis on the introduction of Science into general history than upon the introduction of History into formal science teaching. Nevertheless, we must recognise the important place that historical considerations can take in the formal teaching of science. One function fulfilled by such historical teaching within the scientific curriculum itself is the removal or rather the avoidance of the 'absolute' attitude towards scientific knowledge that is so often purveyed to the elementary student. If trained along historical lines from the first, the student will learn to recognise that science has grown in the past by the operation of forces similar to those which are promoting it in the present, and, moreover, that science has not only grown but has also developed, and that this process of development has been so profound that the whole appearance of the body of scientific knowledge has been changed. This leads naturally to the attitude that what has happened repeatedly in the past may be expected to happen again, and that even what seem our most fundamental scientific conceptions are liable to revision. It is in this willingness to revise opinion that the scientific attitude is to be found. Science is, after all, but conceptual short-hand, and the important thing is not the hand but what is written in it.

There is another aspect from which the study of the History of Science may be of use. There is an idea abroad among the unscientific that scientific discoveries are the result of extreme cleverness. It is often fondly imagined that such discoveries are the result of specially bright ideas on the part of specially bright individuals. Now the History of Science does not confirm this. Bright ideas may be heard in every School and College Debating Society. Few of the exponents of these bright ideas make scientific advances. Very seldom in scientific history has an effective advance been made by one not learned in his particular department. Scientific learning is not always *Book learning*, but it is *Learning* nevertheless. Important biological discoveries have been made only by accomplished naturalists, important mathematical discoveries only by trained mathematicians. It is necessary for such naturalists and mathematicians to receive the tradition of their craft. He who does not is as little likely to do work of value as the star-gazer with no astronomical knowledge. To succeed in science it is necessary to receive the tradition of those who have gone before us. Without them there can be no effectual working. In Science, more perhaps than in any other study, the dead and the living are one. 'We, being many, are one body, and every one members one of another.' Science is a Tradition and Science is One.

§ 4. *Some objections answered*

There is a common idea, a wholly base idea it seems to me, that Science in these latter days has so advanced that no man can survey it as a whole. If it were so—and I for one disbelieve it—that would be good cause to exclude Science from our educational system ; for what does not clarify—which, being interpreted, is but to unify—what does not help a man to ascend the heights of reason that he may behold the world at his feet, cannot aid him in understanding the world in which he lives. If it were so that no man can survey all Science, then the sole plea for Science in education would be its practical application, and Science would be numbered among the crafts and tricks of life. It would be of purely vocational value. It is an unworthy and I believe an untrue view of Science, which would rob it of all spiritual value.

If this view were pressed it would not only prevent the writing of the History of Science, but would also prevent the writing of both History and Science. Who, of his own knowledge, can compass the history of even a single country ? Who, of his own knowledge, can deal with the Animal Kingdom, with the Science of Geometry, or with our knowledge of the Structure of the

Earth ? Yet these limitations have not prevented, and should not prevent, the writing of Histories of England and of Europe, of works on Zoology, of treatises on Mathematics, or of textbooks on Geology. The scope of such books in reference to the direct experience of the individual writer must be effectively infinite. The difficulty of writing them is the difficulty of getting a philosophical grasp of the principles involved, and in obtaining such grasp first-hand knowledge is of primary importance. Yet this knowledge applied in such a field is but a means to an end, and the work must be judged by the grasp of the principles that it sets forth rather than by the mere knowledge of detail that it displays.

The truth is that there never was a time when one man could know *all* that was known about his world. In this respect our age is even as other ages were, and it is a sheer illusion to suppose that it differs from them in this regard. Nor is the advance of Science to be measured by the vast accumulation of observations, but by the degree to which these observations are brought under general laws. The function of Science is to clarify, which is to simplify and ultimately to unify. It is just by its success in unifying our conception of the Universe that the state of Science must be gauged, and not by the number of professors that it employs. I believe that, in fact, a general view *can* be acquired of the state of our scientific knowledge, and that the provision of that view should be an important function of our educational system.

I am aware that in expressing this attitude to scientific knowledge I am in danger of being misunderstood. I am aware that Science *must* involve contact with phenomena, and not mere discourse about phenomena. Teachers of science rightly fear mere theory. They rightly hold that unless the student touches and sees, he is not really learning Science. I entirely share the fear of calling mere book-learning Science, but I think that, so far as the History of Science is concerned, the fear is groundless. It arises, it seems to me, from a confusion of two separate functions of the teacher. On the one hand he has to train his pupil to live his life, on the other hand he has to provide him with a life that is worth living. Practical acquaintance with the Methods of the Sciences is assuredly needed to help us to live our lives. A survey of Science that shall aid us in understanding our World is no less essential to make our lives worth living. For such a survey, historical considerations are not only necessary, but are implicit in the very attempt.

CHARLES SINGER.

I

EARLY SPECULATIONS

§ 1. *Antiquity*

In the days of the ancient Greeks, it was known that amber when rubbed acquires the property of attracting light bodies such as feathers or pieces of wool, and that a certain substance found in the ground has the power of attracting pieces of iron. This substance was termed *Magnesian Stone*, and later *Lodestone*, *Adamant Stone* or *Magnet*. The name 'magnet' was perhaps derived from the district in Thessaly, *Magnesia*, where the material was found in great quantities. As Lucretius says:

> 'The Magnet's name the observing Grecians drew
> From the Magnetic region where it grew.'

Now a very hard stone called *adamant* was already known to the ancients, and it happens that in Latin a similar word *adamare* means 'to have an attraction.' So it came about that late Latin writers connected the two words and termed the Magnesian stone 'adamant.' The confusion passed into our own language. *Lodestone* is so called from the use of the magnet in showing the way: *lode* being the Anglo-Saxon for *way*. The combination of lode and stone is not found, however, until the sixteenth century. In present usage the word Lodestone denotes the naturally occurring ore of iron, Magnetite (Fe_3O_4). The collocation of *lode* and adamant occurs in Shakespeare. Two references to the properties of a magnet in *A Midsummer Night's Dream* are of particular interest:

> 'Your eyes are lodestars, and your tongue's sweet air
> More tunable than lark to shepherd's ear.
>
> 'You draw me, you hard-hearted adamant;
> And yet you draw not iron, for my heart
> Is true as steel.'

The only real property of a magnet known to the ancients was the power of attracting iron, but as time went on, many fabulous tales accumulated concerning it. Thus the magnet became endowed with rare and magic properties. Certain varieties were supposed to have the power of reconciling estranged husbands and wives, and were recommended for love potions. In the presence of diamonds or of garlic, the magnetic stone was thought to lose its virtue, but fortunately the attractive power could be restored by the timely use of goat's blood. It was believed that an iron statue could be made to hang in space if the roof of the building were made of lodestone. The magnet was held to possess medicinal properties, for who did not know that a piece of lodestone held in the hand was a certain cure for the gout! Many such old wives' tales are recorded in Pliny's *Natural History*.

§ 2. *The Middle Ages*

It seems that the use of magnets in showing the direction at sea was known as early as the eleventh century. From that time a suspended magnet or *Compass* began to supersede the older method of guiding a ship by observation of the heavenly bodies. Certain writers explained the setting of a magnet in a constant direction by supposing that it was the stars in the constellation of the Bear that attract the compass needle. By the thirteenth century, the great age of the schoolmen, the fact that a suspended magnet takes up a definite direction, roughly north-south, had become common knowledge. Roger Bacon (1214-1294), for example, wrote about the properties of a suspended magnet. Albertus Magnus (1206-1280) tells us that there are two kinds of magnetic stone, one which points to the north and another to the south: he omits to tell us, however, which is the front and which the back of the magnet, so we are not much wiser.

A discovery of great importance was made in the thirteenth century by one Petrus Peregrinus, or Peter the Pilgrim, a native

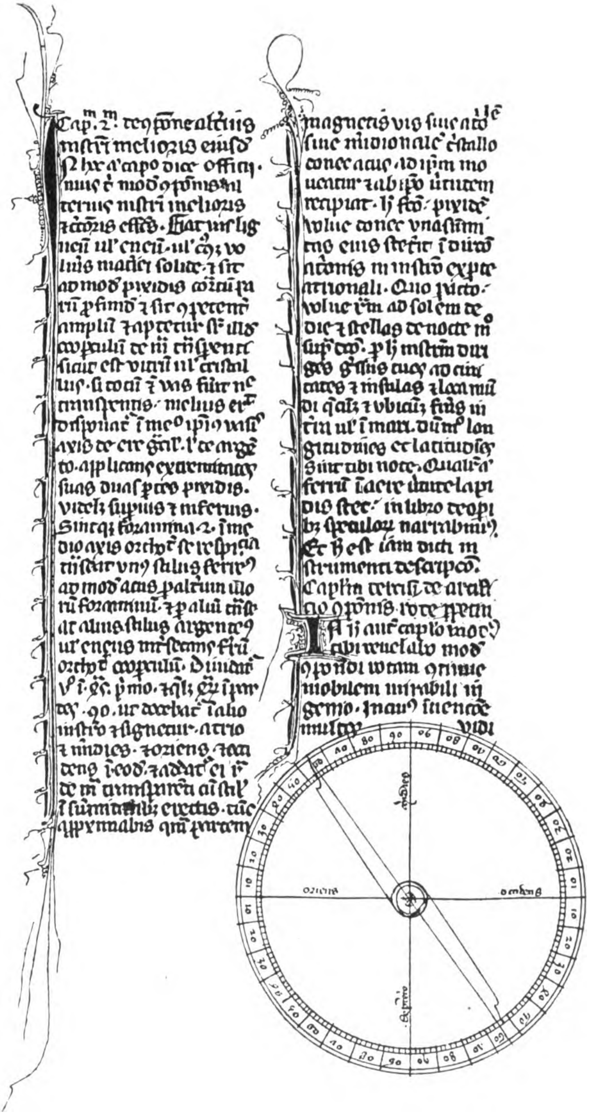


FIG. I.—PAGE FROM *Epistola de Magnete* OF PETER PEREGRINUS.
The diagram has the four directions *meridies* (south) *septentio* (north) *oriens* (east) and *occidens* (west) marked upon it.

of Picardy who took part in the Crusades. This Peter took a piece of natural magnet that had been rounded into a globe, placed a needle on the globe and drew a line showing the direction in which it set. He then moved the needle to another place and again marked its direction, and continued until he had obtained a number of lines passing round the globe. He found that the lines crossed one another at two points at opposite ends of a diameter of the globe, and realised that the lines were like the meridians of the heavenly sphere, and corresponded to those of the earth; he accordingly called the two points *poles*. Roger Bacon in his *Opus Majus*, which was a kind of encyclopaedia of thirteenth-century philosophy, refers to Peregrinus in terms of praise, and calls him Master Peter, quoting one of his experiments in which a wooden cup containing a magnet is allowed to float in a bowl of water. The figure of such an instrument has come down to us in one of the note-books of the great artist Leonardo da Vinci (Fig. 2). Bacon goes on to describe how such a floating magnet always sets itself in the north-south direction, and he says: 'If a thousand times you turn the stone away from that position, a thousand

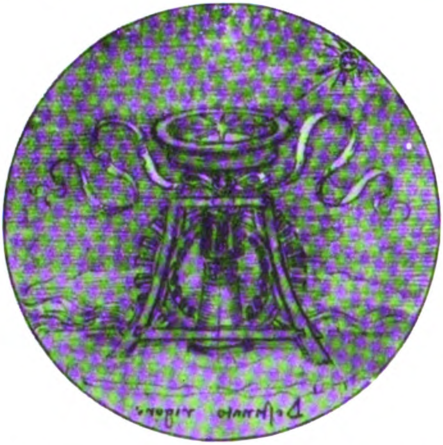


FIG. 2.—LEONARDO'S FLOATING MAGNET.

times will it return by the will of God.' By the sixteenth century, compasses regularly mounted on compass cards were in general use (Fig. 3).

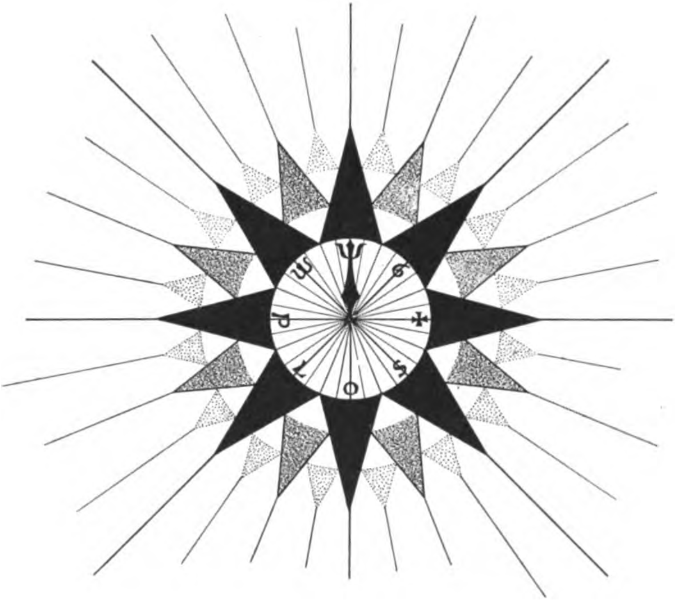


Fig. 3.—Compass Card of Cecco d'Ascoli (1521).

§ 3. *William Gilbert*

These early observations were not followed further until the very end of the sixteenth century. The history of the scientific study of electricity and magnetism dates, in fact, from William Gilbert (1540-1603). This great man was born at Colchester, studied medicine at Cambridge, and later practised in London, where he acted as Physician to Queen Elizabeth. In the intervals of duty at the court, Gilbert carried out the very important investigations that have earned for him the title of 'Father of Magnetism.' He seems to have been devoted to Elizabeth, and

Fuller tells us in his quaint way that 'such his loyalty to the Queen, that, as if unwilling to survive, he died in the same year with her 1603.'

Gilbert gave an account of his experiments in his book published in London in 1600: *De Magnete, Magneticisque corporibus et de magno magnete tellure* ('On the Magnet and magnetic bodies, and on the great magnet, the earth'). This was the first important scientific work published in England. He commences by rejecting the 'idle tales and trumpery' of the magic properties of a lodestone, and proceeds to show how by experiment we may arrive at certain reliable conclusions as to properties of magnets and of the earth. He points out that every piece of lodestone has poles which are 'definite points set in the stone, the primary boundaries of motions and effects, the limits and governors of the many actions and virtues.'

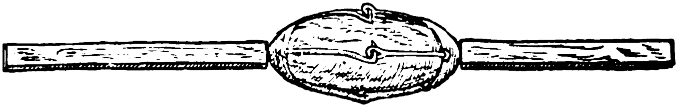


FIG. 4.—ONE OF GILBERT'S LODESTONES.

The first experiment he describes as follows:

> 'Take a powerful lodestone, solid, of a just size, uniform, hard, without flaw: make of it a globe upon the turning tool used for rounding crystals. . . . The stone thus prepared is a true homogeneous offspring of the earth and of the same shape with it. . . . This round stone is called by us a *Terrella*. To find the poles conformable to the earth's, take the round stone in hand and place upon the stone a needle or wire of iron: the ends of the wire move upon their own centre and suddenly stand still. Mark the stone with ochre or chalk where the wire lies and sticks: move the middle or centre of the wire to another place and so on to a third and fourth, always marking on the stone along the length of the iron where it remains at rest: those lines show the meridian circles, or the circles like meridians on the stone or terrella, all of which meet as will be manifest at the poles of the stone.'

Gilbert also describes how the same experiment can be performed by using what he calls a *versorium*, a piece of iron touched with lodestone and then mounted on a pivot. These versoria were thus similar to the small compass needles we use to-day (Fig. 5).

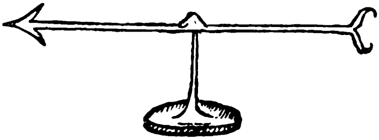


FIG. 5.—GILBERT'S VERSORIUM.

Gilbert then explains how we can distinguish between the poles of a magnet :

> 'The lodestone has the power of directing itself North and South . . . as is proved thus: Place a magnetic stone in a round wooden vessel, a bowl or dish. At the same time place it with the vessel (like a sailor in a skiff) upon water in some large vessel or cistern. . . . Hereupon the stone placed as it were in a ship in the middle of the surface of the still and unruffled water, will at once put itself along with the vessel that carries it, and revolve circularly, until its *austral* pole points to the north, and its *boreal* pole to the south.'
>
> (These words are from *Auster*, the south wind, *Boreas*, the north wind.)

What Gilbert called the austral pole we now call the *north-seeking* or simply the *north* pole ; the boreal pole is now known as the *south-seeking* or *south* pole. By floating two magnets, the poles of which had been previously found, Gilbert was able to show that unlike poles attract and like poles repel each other :

> 'Place the stone which you have seen to have poles clearly distinguished, and marked austral and boreal, in its vessel so as to float. . . . Hold in your hand another stone, the poles of which are also known, in such a way that its austral pole may be towards the boreal pole of the one that is swimming. The floating stone forthwith follows the other stone and does not leave nor forsake it until it adheres. . . . If, however, you apply the austral to the austral, the one stone puts the other to flight.'

Gilbert showed that the above experiment furnished a means of determining the pole of a magnet by seeing whether it was attracted or repelled by the known pole of another magnet. He found also that, if a magnet be cut in half, it acquires poles where it had been neutral before. Having assured himself of the properties of magnets of different shapes by many careful experiments, Gilbert began to enquire why a suspended magnet always sets in a definite direction. From the outset he seems to have ascribed this to the earth, 'Our Great Mother' as he calls her. Yet, like every true scientific investigator, he hesitated to draw conclusions until he had fully satisfied himself of their truth, on experimental grounds. He says :

> 'Before bringing forward the causes of magnetical motions and laying open the proofs of things hidden for so many ages . . . we have to establish and present to the view of the learned our new and unheard of doctrine about the earth. This when argued by us on the grounds of its probability, with subsequent experiments and proofs will be as assured as anything in philosophy ever has been considered and confirmed. . . . The lodestone has poles, not mathematical points, but natural termini of force excelling in primary efficiency by the co-operation of the whole. Now there are poles in like manner in the earth which our forefathers sought ever in the sky : for the sky has an equator, a natural dividing line between the poles, just as the earth has. . . . The heaven like the earth acquires direction and stability towards North and South . . . follows the ascensions and declinations of the earth's poles and conforms exactly to the same and by itself raises its own poles above the horizon or sinks below it.'

Gilbert, then, found that a spherical magnet or *Terrella* (Fig. 6) exhibits all the magnetic effects of the earth itself. Thus a magnet suspended on a terrella takes up a position with respect to it comparable to what we now know as declination and dip. It is a matter on which it is worth quoting him again :

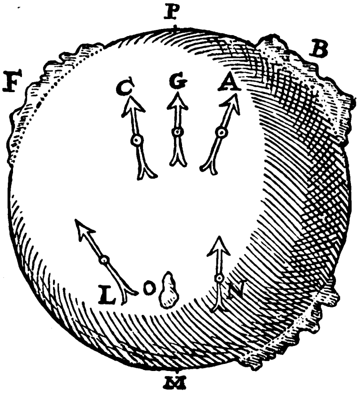


FIG. 6.—ONE OF GILBERT'S IRREGULAR TERRELLAE WITH VERSORIA.

On the Globe of the Earth the Great Magnet,

> 'Just as on the periphery of a terrella, a lodestone is directed to its proper pole : so on the earth's surface are there turnings about, peculiar, manifest and constant on either side of the equator. . . .

The *magnetic dip* (which is the wonderful turning of magnetic things to the body of the terrella) . . . is seen in clearer light to be the same thing upon the earth. And that single experiment, by a wonderful indication as with a finger, proclaims the grand magnetic nature of the earth.' (Fig. 7.)

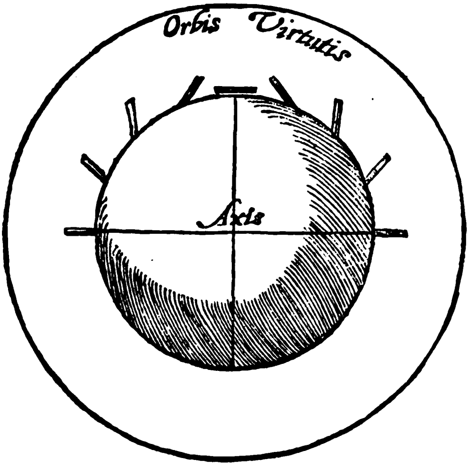


Fig. 7.—One of Gilbert's Terrellae
showing the dip of the magnet in various latitudes.

The *magnetic dip* to which Gilbert refers in this passage is the angle between the axis of a magnet and the horizontal, when the magnet is free to rotate in a vertical plane that includes the magnetic north and south poles (Fig. 8). The dipping of such a needle had been observed by a German investigator about the time that Gilbert was carrying out his researches. The first account of an instrument for measuring the dip, however, was given by Robert Norman, an instrument-maker, in a book *The Newe Attractive*, published in 1581.

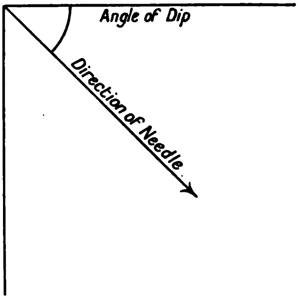


Fig. 8.—Diagram showing Dip.

Norman measured the dip in London and found it to be '71 degrees 50 minutes.' Gilbert saw the phenomenon of the dip was a consequence of the earth's magnetism, but the measurements

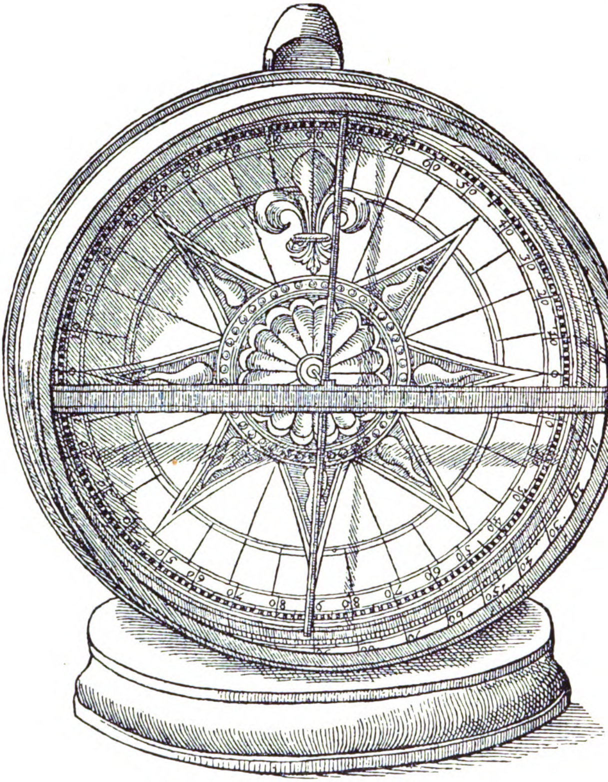


FIG. 9.—GILBERT'S DIP NEEDLE.

themselves interested him and he had a dip circle made, a full description of which he gives in *De Magnete* (Fig. 9).

Let us return for a moment to the mariner's compass. Even before Gilbert it was known that the line in which a compass needle sets itself is not the exact north-south direction as obtained from astronomical measurements. It deviates from that line, and the angle between the two is now known as the *variation* or *declination.* To allow for the variation, compass makers in Gilbert's day were wont to set the direction card below the needle slightly askew. But the variation changes from place to place on the earth's surface, and moreover undergoes a slight change from year to year, so that the correction was never accurate except locally and for a short time. In Elizabethan days so few data were available that the problem of magnetic variation caused navigators considerable anxiety. Realising their difficulties, Gilbert thought that the dip circle might be more reliable than the ordinary compass. His experiments with the terrella had led him to conclude that the lines joining places of the earth's surface where the dip is the same, corresponded with the lines of latitude. It was soon found by navigators, however, that the variations in the dip at places along the same latitude are considerable, and the idea had to be abandoned. As time went, on improvements were made in the construction of the compass. When values of the variation at a large number of places had accumulated, the navigator could apply the necessary empirical corrections to the values read from his chart and thus obtain his magnetic course accurately.

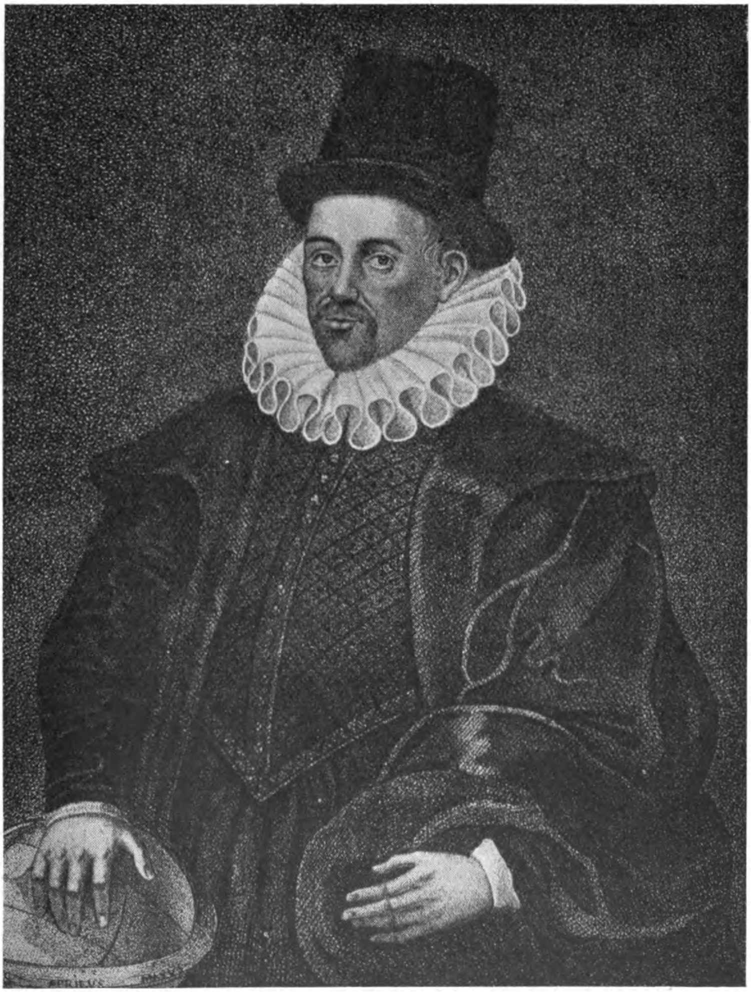
Though Gilbert is known chiefly by his work on magnetism, yet he made many important observations on the behaviour of electrified bodies. These are described in the second book of the *De Magnete* and the practical details contained therein are of great interest. The very word 'electricity' we owe to Gilbert. The name was used by him to describe the strange effects observed when amber is rubbed. The Greek word for amber is *elektron,* the word itself being derived from *elektor*, which means bright. Gilbert noticed that the power of attracting light bodies does not belong to amber alone, but is possessed by other substances, such as glass and certain gems. He recognised two classes of substances, *electrics* and *non-electrics.* He noticed that electrified bodies lose their power when brought near a flame or otherwise heated. He found in the course of his work that many experiments would not work on damp days, a fact known only too well to all students of physics to-day! He constructed a simple piece of apparatus for use as an electroscope by balancing a light needle of non-magnetic material on a pivot so that it moved easily in a horizontal plane.

Thus Gilbert established a number of important facts concerning both electricity and magnetism, and by his insistence on the importance of experimental enquiry, laid sure foundations for the building up of the science. His work was held in great esteem by Galileo, the principal physical experimenter of his age, and in later years he was eulogised by Dryden in the lines:

> 'Gilbert shall live till loadstones cease to draw
> Or British fleets the boundless oceans awe.'

§ 4. *Seventeenth Century after Gilbert*

Except for the work of Gilbert, who died in 1603, there was very little further progress in the study of electricity and magnetism during the seventeenth century. Certain improvements were made in the compass, however, and further data as to the values of the variation and dip at different places were obtained. Halley (1656-1742), the astronomer and the friend of Newton, tried to explain the magnetic variation by supposing that the earth has four poles. William III, impressed by this theory, sent him on a long and fruitless voyage to the Atlantic and Pacific Oceans to find these supernumerary poles. Halley did not succeed in his quest, but his observations were useful for making charts of the magnetic variation at different parts of the earth. Robert Boyle (1627-1691) mentions some electrical experiments in a tract of the year 1675, bearing the title *Experiments, Notes, etc., about the Mechanical Origin or Production of Divers Particular Qualities.* Boyle there tells us that he had observed that false locks of hair when dry are attracted towards the face of another person. Such a phenomenon must have been rather embarrassing in those times when many eminent men of science, including Boyle himself, wore wigs of long curled artificial hair.



WILLIAM GILBERT.

Robert Boyle's greatest contribution to physical theory, however, was one which for a time was outside the department of electrical study. In his book the *Skeptical Chymist* (1661) he cleared away much of the confusion in contemporary theory of the nature of matter. Boyle clearly distinguished between elements and compounds, and taught that heat consists in the motion of the minute particles of a body, ' a various and intestine commotion of the parts among themselves.'

During the eighteenth century considerable progress was made in the study of charged bodies, the department now known as electrostatics. But knowledge of both electricity and magnetism long consisted only of a number of isolated facts, and it was not until more than two hundred years after the death of Gilbert that a definite connection between electricity and magnetism was established. During the later seventeenth and throughout a large part of the eighteenth century many hypotheses were brought forward to account for various physical phenomena, such as those of heat, light, electricity and combustion. These theories often exhibit a strong metaphysical bias. They led to but little in the way of result, and need not detain us here. Science has been defined as a ' description of experience in conceptual shorthand.' It was long, however, before men of science as a body were willing to accept this limitation. In those days there was still a hope that science would give the ultimate explanation of all things, and even in our time there are many who can only think of science as an explanation rather than a redescription of what has been observed.

Robert Boyle.

II

ELECTROSTATICS IN THE EIGHTEENTH CENTURY

§ 1. *The Doctrine of Imponderables in the Eighteenth Century*

THERE were philosophers of the seventeenth century, Newton (1642-1727) among them, who held with Boyle that the essential nature of heat is motion of the minute parts. The close connection between heat and light was clearly recognised. For instance, Newton asked : ' Do not all fixed bodies, when heated beyond a certain degree, emit light, and is not this emission performed by the vibrating motion of their parts ? ' During the time of Newton, there were two rival theories of light, the *Wave Theory*, developed very beautifully by Huygens (1629-1695), and the *Corpuscular Theory*, associated with the name of Newton. The corpuscular view regards light as consisting of minute bodies or corpuscles shot out with great speed. Newton purposely refrained from committing himself to any hypothesis as to the nature of light. Yet because of his refusal to side with Huygens, Newton has been regarded as the champion of the Corpuscular Theory.

After the time of Newton it was usual to speak of imponderable *light corpuscles*. Philosophers gradually became accustomed to the idea of streams of corpuscles leaving a body and yet making no perceptible difference to its weight. The close relationship between light and heat together with the observed fact that a screen of glass cuts off the heating effect of a hot body, while it allows the light to pass through, led to the conception of a heat substance or *caloric*. This substance was supposed to fill up the interstices between the particles of a body, and like the light corpuscles it was supposed to be weightless.

In the hands of Black (1728-1799) the Caloric Theory proved a valuable instrument of research. Black was thereby led to regard heat quantitatively, and so to proceed to actual measurements of specific heat and latent heat. The hypothetical *caloric* and *light corpuscles* came to be included among the elements. Thus there resulted a confusion of thought that lasted until the days of Lavoisier and beyond. Despite the labours of Benjamin Thompson, Count Rumford (1753-1814), in the closing years of the eighteenth century, the caloric theory was not finally abandoned until the recognition of the work of Joule (1818-1889) and the development of the doctrine of energy.

Caloric and light corpuscles were not the only imponderable substances of eighteenth-century physical theory. Another 'imponderable,' *Phlogiston*, the principle of fire, was invoked to explain certain phenomena of combustion. This mysterious substance *Phlogiston* was believed to be present in all inflammable bodies. During the process of burning it was held that the body parted with its Phlogiston. The calcination (*i.e.* oxidation) of a metal was thus regarded as the loss of its Phlogiston. It was the calx (oxide) that was thus regarded as the element, while the substance that we call the elementary metal was held to be a compound.

§ 2. *Conceptions of the Nature of Electricity in the Early Eighteenth Century*

Since the notions of imponderable fluids and subtle atmospheres thus presented no difficulty to the eighteenth-century philosophers, it is not surprising to find electricity described by them as an *effluvium*[1] given off from the charged body, or as an *effluent* stream with an accompanying *affluent* stream, or again sometimes as two subtle fluids and sometimes as one. We can hardly say whether these early philosophers really believed in the existence of a material substance that was at the same time un-weighable. The phrasing of their hypotheses was usually obscure, and no doubt this very vagueness was an effective barrier against further enquiry.

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[1] The *Lexicon Technicum*, 1704, of John Harris describes *effluviums* as 'small particles or corpuscles continually flowing out of all mixt bodies without any sensible diminution of the bulk or weight of the body that emits them.'

Among the most valuable records we have of the state of opinion on the phenomena of heat and electricity at the beginning of the eighteenth century, is that set forth by Wilhelm Jacob 's Gravesande of Leyden (1688-1742).[1]

> ' Fire,' he tells us, ' easily penetrates through all bodies however dense and hard. For we have never yet known any body that by the application of Fire has not been heated in all its points; that is in every part. Fire moves very swiftly, as appears from astronomical observations. Fire unites itself to bodies; for when they are brought to the Fire they grow hot.
>
> . . . If any bodies are violently moved against one another they will grow hot by such a friction and that to a great Degree, which shows that all bodies contain Fire in them: for by rubbing, Fire may be put in motion and separated from a body. . . . There are, besides, several remarkable phenomena arising from Fire contained in bodies, some of which we shall here mention; amongst which there are some as relate very much to Electricity.'
>
> *Definition.* ' Electricity is that Property of Bodies, by which (where they are heated by Attrition) they attract and repel lighter Bodies at a sensible distance.'

Nevertheless, he adopts a materialistic view in some parts of his work. He emphasizes the close connection between heat and light. This view of light as a projection of fast-moving corpuscles, which can be expelled from a heated body, probably led him to regard electricity also as a kind of atmosphere or effluvium. Thus he says:

> ' (*a*) Take a glass tube 15-18 inches long and one inch in diameter and rub it with a cloth, and it will emit light in the dark.
>
> (*b*) This tube heated by rubbing has a very sensible electricity. For if light bodies such as pieces of gold leaf be laid upon a plane and the tube be brought near them, they will be put in motion, attracted, repelled and driven several ways by the tube. The tube acts at varying distances according to the different states of the air. . . . When the air is full of vapours the effect is diminished.
>
> (*c*) If we attend to the foregoing experiments, the following conclusions seem to be naturally deduced therefrom.

---

[1] *Mathematical Elements of Natural Philosophy.* Leyden, 1725, English translation, 1726.

> The glass contains in it and has about its surface a certain atmosphere which is excited by friction and put into a vibrating motion. . . .
>
> The fire contained in this glass is expelled by the action of this atmosphere. . . . This Atmosphere and Fire is more easily moved in a place void of air.'

's Gravesande's work shows the confusion of thought existing at the time. Thus, he regards heat as a motion of the particles of a body, but associates it with a particular kind of material which he later identifies as the *matter of light.* In the early part of his work, however, he had already given the definition of electricity that we have quoted. Later he speaks of electrical effects as due to effluvia peculiar to bodies such as glass and amber.

§ 3. *Some Early Experiments on Static Electricity*

The work of 's Gravesande was translated into English by Jean Théophile Desaguliers (1683-1744), a Huguenot who was educated in England. Desaguliers himself made some important contributions to the practical applications of mechanics. He deserves our notice here for his friendship with one Stephen Gray (died 1736), of whom we know little except that he was a Charterhouse pensioner.

In 1729 Gray communicated to ' Dr. Desaguliers and some other gentlemen ' the details of experiments by which he showed that the properties of a charged body could be conveyed to another body.[1] In other words, Gray was the first to describe the process now known as conduction,[2] by showing

> ' that the Electric Vertue of a Glass Tube may be conveyed to any other bodies, so as to give them the same property of attracting and repelling light Bodies, as the Tube does, when excited by rubbing : that this attractive Vertue might be carried to Bodies that were many Feet distant from the Tube.' Gray continues : ' I have made several attempts on the Metals to see whether they might not be made attractive by the same method as other Bodies were, that is, by heating, rubbing and hammering, but without Success. I then resolved to procure me a large Flint Glass Tube,

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[1] *Phil. Trans.* vol. 37, 1731, pp. 18, 227, 285, 397.

[2] The term ' conductor ' was introduced by Desaguliers after Gray's death.

to see if I could make any farther Discovery with it, having called to mind a Suspicion which some Years ago I had, that as the Tube communicated a Light to Bodies, when it was rubbed in the Dark, whether it might not at the same time communicate an Electricity to them.'

Gray described his experiments in great detail; some of his conclusions are:

'(*a*) That large Surfaces may be impregnated with the Electricity Effluvia.

(*b*) That the Electric Vertue is carried Several Ways at the same Time and may be conveyed to considerable Distances.

(*c*) That the Electric Vertue may be carried from the Tube without touching the Line of Communication, by only being held near it.'

The description that Gray gives of his experiments show that he was a cautious and patient observer, and his results are of great importance. After the publication of his work, philosophers had to modify their ideas about the electric effluvium. Since it could be conveyed from one body to another the effluvium attained the dignity of a separate existence, and we find it called the *electric fluid*. It was still, however, regarded as imponderable, and was still included among the chemical elements.

Despite the close connection recognised between heat and electricity, important differences were also well known. Thus it had been observed that a body could be electrified by conduction without any apparent rise in temperature. Another striking difference between heat and electricity was demonstrated by Gray. In 1729 [1] he took two cubes of oak, one solid, the other hollow, and found that when electrified they produced identical effects. His aim was to find 'whether the Electrick Attraction be proportional to the Quantity of matter in Bodies.' The experiment really showed that electrification is a surface phenomenon. Yet he says: 'I am apt to think that the Electric Effluvia pass through all the interior Parts of the Solid Cube, though no part but the Surface attracts.'

Desaguliers himself performed experiments on Electricity and extended some of Gray's investigations. He showed that bodies can be divided into two main classes: (*a*) Those that are 'electric *per se* in whom a Vertue of attracting and repelling small Bodies at a Distance is inherent'; and (*b*) those that are 'non-electric.' A body of the latter type 'having received electricity will communicate to another Body brought to touch it or only brought pretty near, and that often with a snapping Noise and a small Flash of Light, losing by that means all its own Electricity.'[1] The two types correspond to our non-conductors and conductors respectively.

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[1] *Phil. Trans.* vol. 37, 1731, p. 35.

§ 4. *The First Mention of Different Electrifications*

At about the time when Desaguliers and Gray were working in England, a theory of electricity was brought forward by a Frenchman, Charles-François du Fay (1698-1739). His view bears some resemblance to that of the famous *Two Fluid Theory* over which, in after years, a vast controversy waged.

After describing a number of experiments similar to those of Gray and including the electrification of a child suspended by silk cords, du Fay says:

> 'Chance has thrown in my way another principle, more universal and remarkable . . . which casts a new Light on the subject of electricity. This principle is that there are two distinct Electricities, very different from one another; one of which I call vitreous Electricity and the other resinous Electricity. The first is that of Glass, Rock-Crystal, Precious Stones, Hair of Animals, Wool and many other bodies. The second is that of Amber, Copal,[2] Gum-Lac, Silk, Thread, Paper and a vast number of other substances. The characteristic of these two Electricities is that a Body of the Vitreous Electricity, for example, repels all such as are of the same Electricity; and on the contrary attracts all those of the resinous electricity. . . . This Principle very naturally explains why the ends of Thread, of Silk or Wool recede from one another in the form of a Pencil or Broom when they have acquired an electrick Quality.'[3]

Du Fay was superintendent of the Gardens of Louis XV, and thus came in contact with the Court. An interest in electrical experiments was shown by a more elevated member of the Court, the Abbé Jean Antoine Nollet (1700-1770), teacher of Natural Philosophy to the Royal Family. Nollet regarded electrical phenomena as due to the movement in opposite directions of two currents of a fluid, which he supposed present in all bodies. Electrification by friction he interpreted as an escape of this fluid from the body. The escaping fluid formed an *effluent stream*, but at the same time an *affluent stream* entered the body from outside. Light bodies were attracted, he thought, because they were caught in the whirls set up by these streams. The human mind seems to crave for 'explanations,' and Nollet's teachings offered a plausible interpretation of electrical phenomena which caught the popular fancy.

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[1] *Phil. Trans.* vol. 41, part ii. p. 634.

[2] A resinous gum.

[3] 'A letter from Mons. Du Fay, F.R.S., and of the Royal Academy of Sciences at Paris, to his Grace Charles Duke of Richmond and Lenox concerning Electricity.' *Phil. Trans.* vol. 38, 1734, p. 258.

§ 5. *The Storing of Electricity. Invention of the Leyden Jar*

The fact that a damp atmosphere often rendered futile the best efforts of the experimenter led a professor at Leyden, Pieter van Musschenbroek (1692-1761), to apply himself to the problem of storing electrical charges. He regarded the leaking away of the charges as due to air conduction. To prevent it the charged body should, he thought, be surrounded by a non-conductor. He suspended a bottle of water from a gun barrel by means of a metal wire passing through the cork. The gun barrel was hung up by silk threads and charged by means of an electrified glass body brought near (Fig. 10).

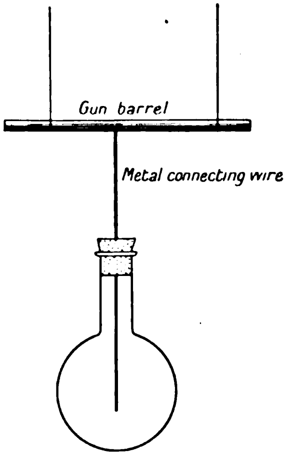

Fig. 10.—The first Leyden Jar.

This charge, he considered, would pass into the water, the glass bottle forming the non-conductor that would protect the charge. Nevertheless, when he touched the gun barrel with one hand and the glass bottle with the other he felt a shock, which frightened him so that he said he ' would not take another for the Kingdom of France.'

Musschenbroek's experiment was soon repeated, notably by the Abbé Nollet, who, in the King's presence, passed a discharge through a line of guards holding hands. Afterwards, when the men were found to suffer no ill effects, he conducted the experiment on a still larger scale, with several hundred Carthusian monks standing in a long line. The story relates that they gave a sudden spring when the contact was completed. Musschenbroek's apparatus was called by Nollet the *Bouteille de Leyde*, or *Leyden Jar*, by which name it has ever since been known.

The apparatus for these early experiments on electricity was easily procurable, and thus electricity became a happy hunting-ground for the amateur. When news of the Leyden jar experiments reached England many people began trying the effects of electric shocks on themselves and others. Some important observations were made by William Watson (1715-1787), a London apothecary who afterwards rose to eminence in the medical profession. In a Memoir of 1746 he suggested that electricity is present in all bodies, and that the electrification of a body such as glass or amber means that electricity is accumulated at the expense of some other body, which thereby loses an equal quantity.[1] (Fig. 11.)

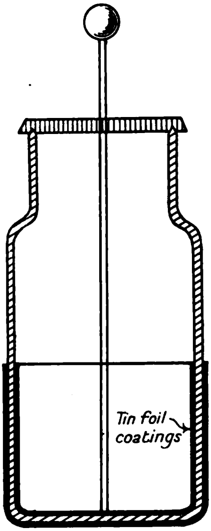

FIG. 11.—WATSON'S LEYDEN JAR.

This same idea was put forward independently by Benjamin Franklin (1706-1790) of Philadelphia, whose book fell into the hands of the Abbé Nollet. The Abbé, in great indignation, thought that Franklin's book had been written with the express purpose of contradicting his own theory. He immediately began to justify his views and to refute those of Franklin with great vigour. Yet it was Franklin's theory which was to prove to be fruitful and suggestive for future workers, while the Abbé's in-going and out-going streams were soon forgotten.

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[1] *Phil. Trans.* vol. 44, 1746, p. 718.

§ 6. *Benjamin Franklin*

Benjamin Franklin was born in Boston, Massachusetts. His father, who was a soap and candle maker, had come from England to seek religious freedom. When ten years old Benjamin was taken from school. He entered his father's shop as an apprentice, and spent two years in running errands, filling soap moulds and cutting wicks for candles. The life was so distasteful to him that he abandoned it to become a printer's apprentice. It was then that his real education began in the world of books.

After some years Franklin opened a shop of his own in Philadelphia. Here he attracted the notice of the Governor, who commissioned him to visit England for the purpose of buying material for a Government printing-press. On his return to Philadelphia, Franklin's business prospered and he became a prominent citizen. He came to play an important part in politics and diplomacy. His work on electricity was not begun until after the age of forty He had seen some few experiments performed by a travelling lecturer, and the subject so fascinated him that he determined to try the effect himself. An account of Franklin's early experiments is given in a number of letters to a friend in London. In the first letter Franklin refers to ' M. Musschenbroek's wonderful bottle ' (that is the Leyden jar). He says that the electrical fire is accumulated on the surface of the bottle, forming an electrical atmosphere round it. His explanation of the action of the Leyden jar is as follows :

> ' At the same time that the wire and top of the bottle, etc., is electrified positively or plus, the bottom of the bottle is electrified negatively or minus, in exact proportion ; *i.e.* whatever quantity of electrical fire is thrown in at top, an equal quantity goes out of

BENJAMIN FRANKLIN

> the bottom. . . . The equilibrium cannot be restored in the bottle by inward communication or contact of the parts ; but it must be done by a communication form'd without the bottle between the top and bottom, by some non-electric touching both at the same time.' [1]

Let us see how Franklin was led to his hypothesis that electricity is an element present in all matter, an idea suggested independently by Watson in England. Franklin reasons thus : Let a person *A*, standing on wax so that the electricity cannot pass from him to the ground, rub a glass tube. Then if another person *B*, also standing on wax, passes his knuckle *near* the tube, then both *A* and *B* will be electrified and so capable of giving a spark to a third person *C* standing on the floor. But if *A* and *B* touch during or after the preliminary rubbing they are not electrified. Franklin interpreted the experiment by supposing that the rubbing transfers some of *A*'s electricity to the glass, which passes to *B* so that *A* has a deficiency and *B* a superfluity of electricity, so that when the person *C* approaches, the distribution of electricity is equalized by the passage of a spark. But if *A* and *B* touch, electricity flows between them until the normal quantity resides on both and they are each therefore unelectrified.

Franklin's theory of electrification is usually referred to as the One Fluid Theory. He uses the terms *positive* and *negative* to denote superfluity and deficiency of the electrical fluid. Nevertheless, it is important to notice that the recognition of two kinds of electrification involves no hypothesis as to the nature of electricity itself. Thus, to call a body positively electrified if repelled by a glass rod rubbed with silk, and to call a body negatively electrified if repelled by sealing-wax previously rubbed with fur, is simply a matter of choice of the terms used to describe observed phenomena. An assumption was made when he spoke of the ' electrical fire ' existing in all matter in its normal state, and when he ascribed electrical effects to the action at a distance of the particles of this subtle electric fluid.

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[1] *New Experiments and Observations on Electricity.* London, 1750. Letter I.

Convincing proof that positive and negative charges always appear simultaneously and in equal amounts, was not given until the work of Faraday in the nineteenth century. Yet Franklin certainly had the conception of the conservation of the electrical charge.

In his first letter he writes :

> ' So wonderfully are these two states of Electricity the plus and the minus combined and balanced in this miraculous bottle ! Situated and related to each other in a manner that I can by no means comprehend ! . . . Here we have a bottle, containing at the same time a *plenum* of electrical fire, and a *vacuum* of the same fire, and yet the equilibrium cannot be restored between them but by a communication *without* ! though the plenum presses violently to expand, and the hungry vacuum seems to attract as violently in order to be filled.'

In another letter Franklin describes the effect of points ' in drawing off and throwing off the electrical fire.' He made use of metal points in drawing lightning from the clouds during a thunderstorm. The metal points were attached to a kite, and the charge conducted along the line by which the kite was held. Franklin argued that if a pointed piece of metal were attached to a long metal rod, passing into the ground, the electricity of a lightning flash would be led away harmlessly.

This led to his invention of the lightning conductor. Franklin's success in showing lightning to be an electrical phenomenon brought him world-wide fame. The use of the lightning conductor was denounced as interfering with the wrath of God by well-meaning divines, and it may be that advertisement from the pulpit added to Franklin's fame !

§ 7. *Priestley and the Law of Inverse Squares*

The early workers on the subject of electricity seem to have been satisfied with qualitative experiments. Until the time of Priestley (1733-1804) there was no investigation of the relation of the force between two electrified bodies and the distance that separates them. Priestley is well known for his researches in chemistry, but his pioneer contributions to the subject of electricity have not always received the recognition they deserve. Franklin met him when on a visit to England. The two men became friends, and Franklin suggested certain problems for further consideration. In 1766 Priestley showed experimentally that when a hollow metal vessel is electrified, there is no charge on the inner surface. From this he inferred the law of force which he published the next year.

> 'May we not infer from this experiment,' he says, 'that the attraction of electricity is subject to the same laws with that of gravitation, and is therefore according to the square of the distances; since it is easily demonstrated that were the earth in the form of a shell, a body in the inside of it would not be attracted to one side more than another?'[1]

Priestley's recognition of the law of inverse squares was a brilliant inference. It was afterwards verified by direct measurement (see p. 36).

§ 8. *Some Early Electrical Machines*

For many years the experimenter obtained electrical charges simply by rubbing pieces of amber, glass or sulphur on his coat. Otto von Guericke (1602-1686), however, devised a means of obtaining larger charges. He mounted a sulphur ball so that it could be spun round, while his own hand, pressed against the ball, produced the necessary friction. An improvement on this primitive apparatus was made by Hauksbee the elder (d. 1713?). He used a glass globe, turned by means of a driving wheel and rubbed with the hand (Fig. 12). Another type of machine was made by William Watson. He used several glass globes and rubbers of leather (Fig. 13). Priestley himself designed a machine[2] which was fitted with adjustable supports for the globe and rubber (Fig. 14). In this way the heating due to the friction could be considerably reduced.

The early experimenters had noticed that one body may be electrified by another even when there is no contact between

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[1] *The History and Present State of Electricity with Original Experiments*, London, 1767, p. 732.

[2] *Ibid.*, p. 112.

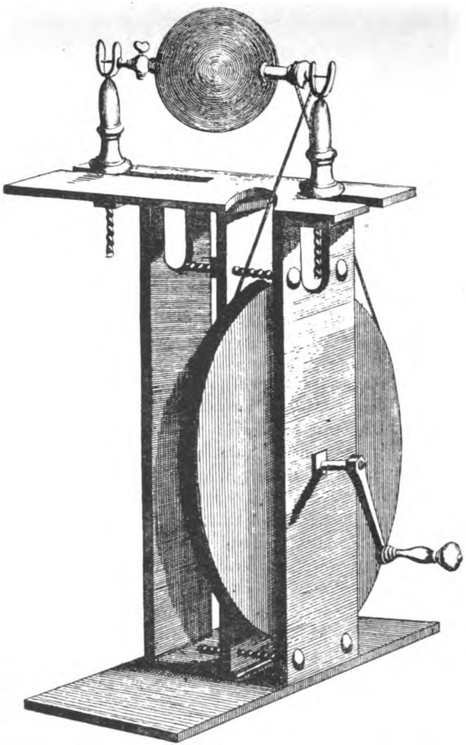

FIG. 12.—HAUKSBEE'S ELECTRICAL MACHINE.

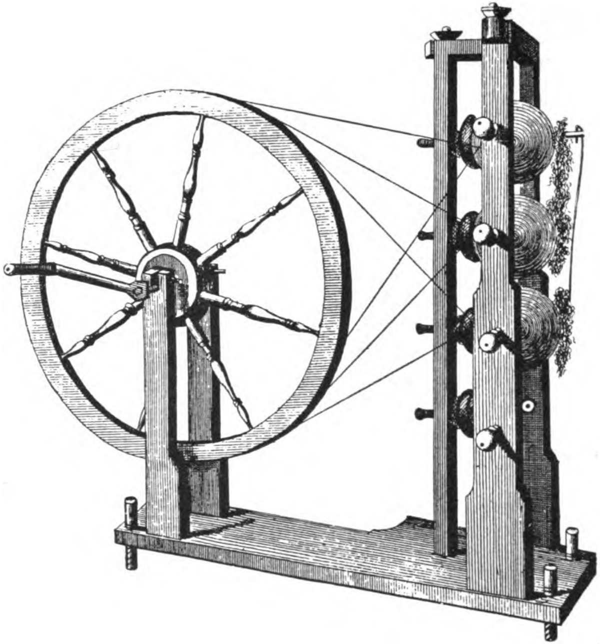

FIG. 13.—WATSON'S ELECTRICAL MACHINE.

them. Such electrification is said to be due to *influence* or *induction*. A simple influence machine was made in 1789 by Abraham Bennet (1750-1799), the inventor of the gold-leaf

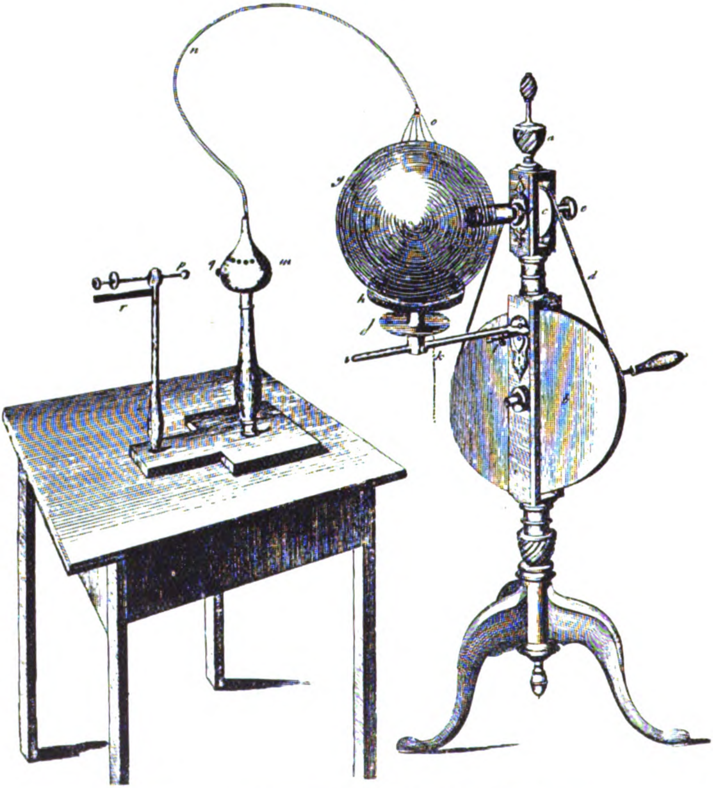

FIG. 14.—PRIESTLEY'S ELECTRICAL MACHINE.

electroscope. All modern electrical machines depend on the principle of influence, a small initial charge being continually replenished by the transformation of mechanical into electrical energy.

§ 9. *The Work of Cavendish*

A contemporary of Priestley was the Hon. Henry Cavendish (1731-1810). He was the elder son of Lord Charles Cavendish, brother of the third Duke of Devonshire. Little is known of the details of Cavendish's life. He never married, and for many years lived with his father, from whom he received a very moderate allowance. He shunned ordinary social intercourse, but occasionally entertained a group of scientific friends at his house. He lived for many years in a house at Clapham Common, having at the same time a town house in Bloomsbury and a library in Dean Street, Soho. In later life he inherited a large fortune, which made him one of the richest men of his time. His methodical habits were such that not only did he enter in a loan book all the books he lent to friends, but he kept a written record of all the books he took down from the shelves for his own use.

The scientific work of Cavendish is remarkable for its range and accuracy. He lived for his work alone, and seemed not only indifferent to fame, but to have no interest in the work of other men. Many of his most valuable investigations were unknown to his contemporaries, and it was not until about the middle of the nineteenth century that the real value of his work was realised. At that time Lord Kelvin found some important numerical results in Cavendish's manuscripts, and urged their publication. The work of editing was undertaken by Clerk Maxwell (see p. 129),[1] and thus many of Cavendish's investigations were at last brought to light.

Nevertheless, even the few papers published during his lifetime were sufficient to place Cavendish among the greatest men of science of the time. His genius was recognised by Thomas Young (1773-1829), himself a man of profound insight in almost every branch of science. Young's own experiments on diffraction were of great importance in the revival of the Wave Theory of Light in the early nineteenth century.

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[1] *The Electrical Researches of the Hon. Henry Cavendish*, edited by J. Clerk Maxwell. Cambridge, 1879.

In 1771 Cavendish presented to the Royal Society a memoir entitled *An attempt to explain some of the phenomena of Electricity, by means of an elastic fluid.*[1] He begins with a statement of his hypothesis, then proceeds with his mathematical reasoning, and finally discusses how far the results he deduces agree with those obtained by experiments. The memoir opens thus:

> 'There is a substance which I call the electric fluid, the particles of which repel each other and attract the particles of all other matter, with a force inversely as some less distance than the cube. . . . For the future, I would be understood never to comprehend the electric fluid under the word matter, but only some sort of matter. . . . All bodies in their natural state, with regard to electricity, contain such a quantity of electric fluid, interspersed between their particles, that the attraction of the electric fluid in any small part of the body on a given particle of matter shall be equal to the repulsion of the small part on the same particle. A body in this state I shall call saturated with electric fluid: if the body contains more than this quantity of electric fluid, I call it overcharged: if less, I call it undercharged. This is the hypothesis; I now proceed to examine the consequences which will flow from it.'

He then proceeds to a calculation of the force acting on a particle within a hollow spherical shell. He quotes Newton's proof[2] that in a hollow shell, if the repulsion between the particles of matter is inversely as some higher power than the square, any particle will be impelled *towards* the centre, whereas if the repulsion is inversely as some lower power than the square, the particle will be impelled *from* the centre.

The inverse square law as applied to electrical attractions and repulsions, was implied in Cavendish's early writings, and he supplied an indirect proof which we shall consider later. The most important researches of Cavendish were recorded in his manuscripts. The description Cavendish gives of his experiments in these manuscripts are models of clear exposition, so that it is possible that he intended these papers for publication.

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[1] *Phil. Trans.* vol. 61, 1771, pp. 584-677.

[2] *Principia*, Lib. 1, Prop. 70.

He gives interesting experimental details, discussing the possible sources of error and explaining the precautions to secure accuracy.

The apparatus of Cavendish was of the simplest, yet many of his results agree closely with those obtained by later observers using much more sensitive measuring instruments. As an experimenter, Cavendish must have been patient, skilful and ruthlessly critical of his own results. His Leyden 'jars' were flat pieces of glass with coatings of tinfoil. One piece of tinfoil could be electrified and the other connected to earth, such an arrangement constituting what we now call a *condenser*. He had a large number of such condensers made up in sets of varying size.

Cavendish introduced the term *degree of electrification*, giving it the significance we now attach to the term *potential*. His physical interpretation of the degree of electrification was that of compression or pressure. The capacity of a condenser we now define as the ratio of the charge to the potential. He made many measurements of the capacity of different condensers. The values he gave for the capacities were expressed in the rather curious unit, *inches of electricity*. A condenser with a capacity of *three inches* had a capacity equal to that of a sphere of three inches diameter, and so on. He found that the capacity of a condenser depends on the nature of the insulating substance used, varying according as glass, wax, sulphur or air be employed. By using the same pair of plates and comparing the capacities with different insulating substances, with the capacity when air formed the medium, Cavendish obtained constants for glass, wax, etc. In this way he anticipated the experiments of Faraday on specific inductive capacity.

Cavendish made important investigations of the conducting power of different materials. In a memoir on the Torpedo or electric fish, he refers to the discharging of a Leyden jar by a wire passing from the inner to the outer coating. He explains that a person holding the wire with both hands feels no shock because 'metals conduct surprisingly better than the human body.' Thus he had the conception of resistance and of a current dividing itself between two paths inversely as the resistances. 'It appears,' he says, 'from some experiments of which I propose shortly to lay an account before this Society, that iron wire conducts about 400 million times better than rain or distilled water, that the electricity meets with no more resistance in passing through a piece of iron wire 400,000,000 inches long, than through a column of water of the same diameter only one inch long. Sea water, or a solution of sea salt, conducts about 720 times better than rain water '[1] The promised details of the experiments did not appear, but it is most remarkable that such results could be obtained without more refined apparatus.

In the experiments on conducting powers Cavendish simply compared the intensity of the shock he felt on different occasions. He must surely have submitted himself to shocks many times before he obtained any consistent results. Should he not rank among the martyrs of science?

We have seen how Cavendish discussed the law of force between particles of the electric fluid in his first memoir to the Royal Society. He afterwards gave an experimental proof of the law of inverse squares. The experiment was designed to test whether, when a hollow globe is electrified, there is any charge on a smaller globe placed inside. He says:

> 'I took a globe 12.1 inches in diameter and suspended it by a solid stick of glass run through the middle of it as an axis and covered with sealing wax. . . . I then enclosed this globe within two hollow pasteboard hemispheres 13.3 ins. diameter and about $\frac{1}{20}$ ins. thick. . . . Having done this I electrified the hemispheres by means of a wire communicating with the positive side of a Leyden vial.' (Fig. 15.)

The pasteboard hemispheres were mounted on a wooden framework which opened and closed like a book. These hemispheres were connected to the inner sphere by a piece of metal. They were then brought together to form a closed outer sphere and electrified. The wire connecting the inner and outer spheres was now removed with insulating tongs. The framework was then opened out again and the inner sphere tested for signs of electrification. The detecting instrument Cavendish used consisted merely of a pair of cork balls mounted on straws or linen threads. He repeated the experiment many times, but found no traces of electrification on the inner sphere, but only on the outer sphere.

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[1] *Phil. Trans.* vol. 66, 1776, p. 196.

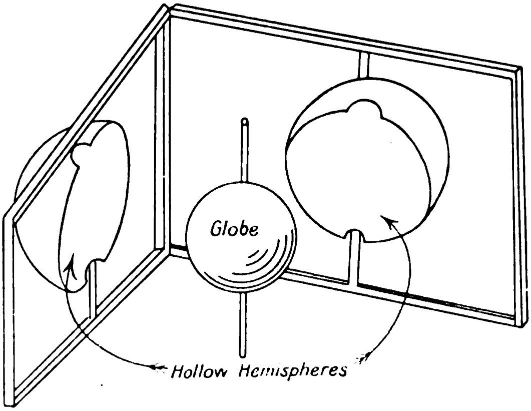

FIG. 15.—HOLLOW HEMISPHERES USED BY CAVENDISH.

We have seen how Priestley arrived at the inverse square law from the analogy between electrical attractions and those of gravitation, and how it was this analogy which first led Cavendish to the same result. The following proof shows how the inverse square law follows from the fact that there is no electrification within a hollow charged conductor (Fig. 16).

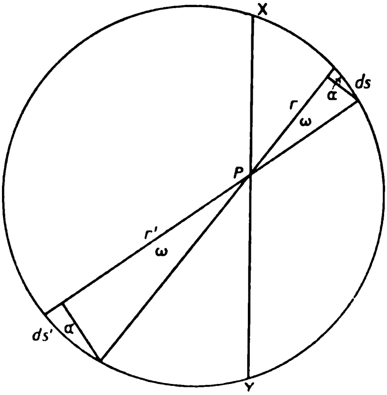

FIG. 16.—ILLUSTRATING THE FORCE AT A POINT within a hollow charged conductor.

Let P be any point inside a hollow charged sphere. Construct a cone having its apex at P and with small solid angle ω. Let the cone cut the surface in two small areas ds, ds'. The perpendicular sections of the cone at ds and ds' are $r^2\omega$ and $r'^2\omega$ respectively, and since these sections make an angle α with the surface, the areas ds and ds' are $\frac{r^2\omega}{\cos\alpha}$ and $\frac{r'^2\omega}{\cos\alpha}$ respectively. Calling the charge on unit area σ and supposing that the force varies inversely as the *nth* power of the distance, we have the force at P due to $ds = \frac{\sigma r^2\omega}{r^n \cos\alpha}$ and the force due to $ds' = \frac{\sigma r'^2\omega}{r'^n \cos\alpha}$. The forces are clearly equal when $n=2$. If n is greater than 2 the force due to ds is greater than that due to ds' because $\frac{1}{r^{n-2}}$ will be greater than $\frac{1}{r'^{n-2}}$, and all the elements on the same side of the plane XY will give rise to components at P greater than those due to corresponding elements on the other side of the plane XY, since for all these pairs $r<r'$. Similarly, if n is less than 2 there will still be a resultant force at P, though in the opposite direction.

§ 10. *Later Experiments in Continuation of the Work of Cavendish*

In the above proof we supposed the force to vary inversely as the *nth* power of the distance, and, according to the law of inverse squares, n will be equal to 2, and consequently $(n-2)=0$. The experimental verification of the law will therefore depend on the nearness with which n can be shown to approximate to 2. Cavendish computed that with his apparatus $n-2$ could not be greater than $\frac{1}{50}$. In 1870 Clerk Maxwell (1831-1879) repeated the experiment of Cavendish, using more refined apparatus. He computed that the sensitiveness of his electrometer was such that n could not differ from 2 by more than $\frac{1}{21600}$. The law of inverse squares he therefore regarded as established within the margin of this minute experimental error.

A direct measurement of the force between two small charged bodies was made by Charles Augustin Coulomb (1736-1806) with the aid of the piece of apparatus now known as the *torsion balance* [1] (Fig. 17). The greater part of Cavendish's work on electricity was unknown to his contemporaries. Thus it came about that the development of electrical theory during the last decades of the eighteenth century was due mainly to Coulomb. In his experiment Coulomb compared the repulsion between two gilded pith balls at varying distances. One ball was fixed, the other attached to an arm. The movement of the arm was controlled by the torsion of the wire *AB* as shown in the diagram. By turning the milled head *A*, the repelled pith ball could be brought back to its original position. The angle through which the head was turned gave a measure of the repulsive force.

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[1] *Histoire de l'Acad. des Sciences*, 1788, Fifth Memoir, p. 421.

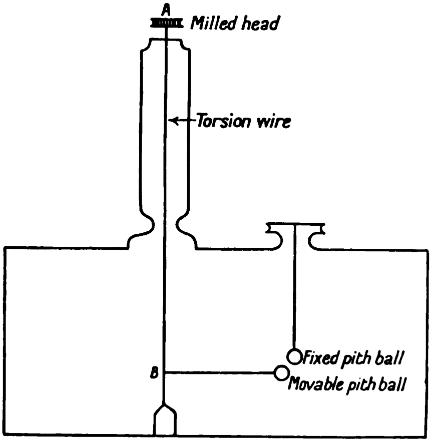

FIG. 17.—TORSION BALANCE.

The torsion balance was invented independently by a young Fellow of Queen's College, Cambridge, John Michell (1724-1793), who afterwards became the rector of a country parish in Yorkshire. Michell was the friend of Priestley and of Cavendish. He suggested the method for finding the density of the earth usually known as the 'Cavendish experiment.' Franklin's principle of the conservation of electric charge and the recognition of the inverse square law had by this time raised the study of electricity to the dignity of an exact science.

The *One Fluid Theory* of Franklin was modified by Francis Ulrich Aepinus (1724-1802). Aepinus held the Chair of Natural

Philosophy at St. Petersburg. He denied altogether the existence of effluvia or atmosphere round a charged body, and concluded that in some way electricity can act across space. Coulomb also dispensed with the electrical effluvia, and developed his reasoning on the hypothesis of two fluids. 'Whatever be the cause of electricity,' he says, 'we can explain all the phenomena by supposing that there are two electric fluids, the parts of the same fluid repelling each other according to the inverse square of the distance and attracting the parts of the fluid according to the same inverse square law.'[1]

Much controversy, however, still raged round the question of whether electricity should be considered as one or as two fluids. But gradually, as the mathematical elaborations became more engrossing, physicists ceased to trouble themselves as to the exact nature of the electrical fluid. Either hypothesis served to interpret observed facts. The *Two Fluid Theory* lent itself better to mathematical treatment, however. It was consequently adopted by the French physicists who were the followers of Coulomb. In the hands of Poisson (1781-1840) and Laplace (1749-1827), the outstanding figures of the French School, this theory became the basis for an analytical treatment in which electrical forces were regarded as acting at a distance. The triumph of the 'action at a distance' principle, applied to the theory of gravitation by Newton and developed by Lagrange and others, no doubt led to the adoption of the principle in electrical theory. The mathematical super-structure grew apace in spite of the fundamental difficulty in imagining two fluids which could exert powerful forces across intervening space and yet at the same time possess no weight. As Sir J. J. Thomson has said: 'The physicists and mathematicians who did most to develop the fluid theories confined their attention to questions which involved only the law of forces between electrified bodies and the simultaneous production of equal quantities of plus and minus electricity, and refined and idealized their conception of the fluids themselves until any reference to their physical properties was considered almost indelicate.'[1]

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[1] *Mémoires de l'Academie des Sciences*, 1788, p. 561.

The principle of 'action at a distance' dominated electrical theory for many years. Not till after the time of Faraday did physicists turn their attention to the medium as a means for the transmission of electrical force. The results of Faraday's work we shall discuss in a later chapter. Meanwhile, we must consider some important discoveries that were made during the closing years of the century. These discoveries, which opened up an entirely new field for investigation, served to link together phenomena hitherto regarded as diverse.

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[1] Silliman Lectures, 1903.

III

THE ELECTRIC CURRENT

§ 1. *Galvani*

UNTIL the end of the eighteenth century, the existence of what we now know as the electric current was unrecognized. The only electric phenomena known were concerned with charged bodies. The flash of the discharge, the crack of the spark, were perpetual sources of wonder and delight, and provided excellent lecture experiments. The early workers, instead of breaking fresh ground, almost confined their attention to improving their static electrical machines and searching for startling effects.

The first observation of the effect of an electric current was one of the few instances in the history of science of a purely accidental discovery. Luigi Galvani (1737-1798), for many years Professor of Anatomy at his native city of Bologna, was investigating the susceptibility of nerves to irritation. He had dissected a frog and left it on a table near an electric machine. An assistant happened to touch the inner crural nerve with a scalpel. Suddenly the frog gave a kick. The presence of the electrical machine led Galvani to suppose that it played some part in the proceedings.

Knowing that lightning was an electrical phenomenon, Galvani thought it would be a simple matter to experiment in his garden and see if a similar effect could be brought about during a thunderstorm. He prepared a number of frogs and fastened the legs by means of brass hooks passing through the spinal marrow to an iron lattice outside his house. He observed convulsive kicks occasionally on fine days and more frequently during thunderstorms. Now when he pressed the brass hooks against the iron lattice he always noticed contraction of the frog's muscles, whatever the apparent electrical state of the

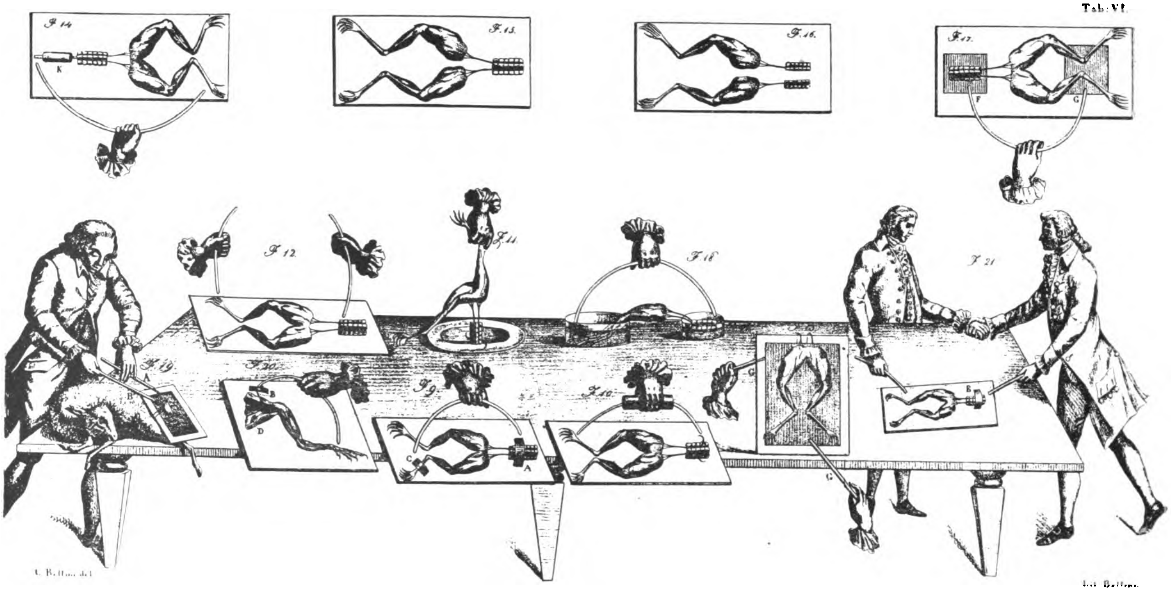

FIG. 18.—GALVANI'S EXPERIMENTS.

atmosphere. Consequently, Galvani, as a cautious experimenter, eliminated the atmospheric factor by the simple expedient of working indoors.

Galvani now found to his delight that when the frog was placed on an iron plate and the brass hook pressed firmly against this plate, violent contractions of the muscles always ensued. He thus convinced himself that the necessary condition for the kick is the contact of two different metals with the nerves and muscles. Galvani considered the effect comparable to the discharge of a Leyden jar. He supposed that there is a natural excess of the electric fluid in the living tissue, and that this fluid is conveyed

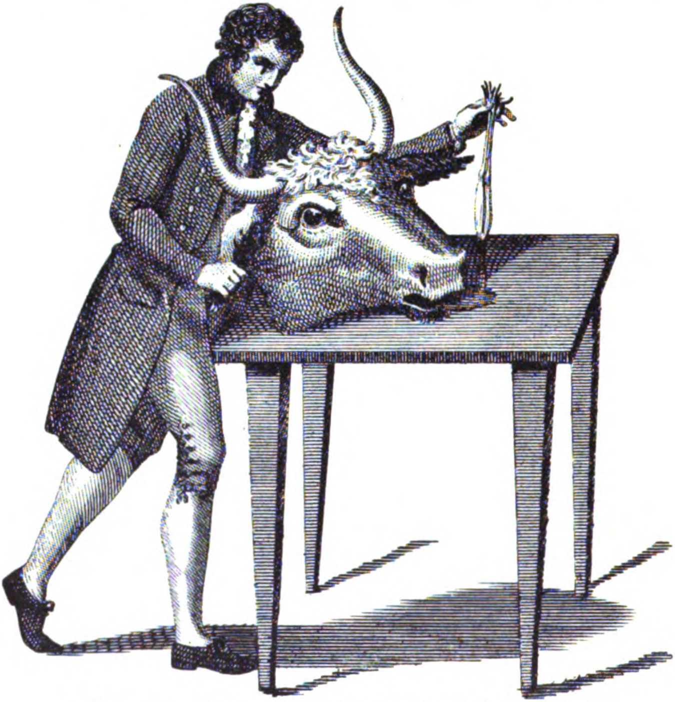

FIG. 19.—FROM AN EARLY WORK ON GALVANISM showing the supposed production of animal electricity.

from the nerves to the muscles through the metallic conductor (Fig. 18). When the results were published there was a great stir in the learned world. Many thought that a new kind of electricity had been discovered, and dubbed it *animal electricity*, or *galvanism* (Fig. 19).

§ 2. *Volta*

Galvani's conclusions were challenged by Alessandro Volta (1745-1827). This observer supposed the effects to be due simply to the contact of two different metals with the 'warm humours' of the living body, and not to the existence of any electric fluid in the animal tissues.[1] Volta was Professor of Natural Philosophy at the University of Pavia, and his interest in the new phenomena led him to a great discovery. Meanwhile popular interest in Galvani's experiments died down. Disappointed and involved in political troubles, Galvani died brokenhearted in 1798. Less than two years later Volta announced that he had found a means of increasing electrical effects by using a number of pairs of metal plates instead of only one pair. He tells us that he used a number of discs of metal separated by skin or any porous substance well moistened. One of the metals used was always zinc, the other sometimes copper and at other times silver. Such a set of plates or discs became known as a *Voltaic pile*.

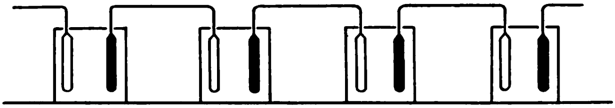

FIG. 20.—VOLTA'S CROWN OF CUPS.

He afterwards used cups containing brine, arranging the metals alternately and connecting them as in the diagram (Fig. 20). Thus was constructed the *couronne de tasses*,[2] which we now know as the Voltaic battery. Volta found that when the end plates were touched simultaneously by the fingers a shock was felt similar to that of a Leyden jar. But there was this important difference. When the two coats of a Leyden jar are connected by any kind of conductor, the momentary effect discharges the jar so that it can no longer give a shock or spark. In the case of his crown of cups, however, the shock could be obtained over and over again. It thus seemed that Volta had discovered a way of obtaining an inexhaustible supply of electrical force. The new discoveries attracted the interest of Napoleon, who sent for Volta to show his experiments in Paris. The Emperor of Austria made Volta Director of the Philosophical Faculty at Padua, and in later life he lived in honourable retirement in his native town.

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[1] *Phil. Trans.* 1793, pp. 10, 27: 'Account of some discoveries made by M. Galvani of Bologna with Experiments and Observations on them.'

[2] *Phil. Trans.* 1800, p. 411.

§ 3. *Investigations in England*

The news of Volta's discovery was communicated to Sir Joseph Banks, then President of the Royal Society. A month later the first large Voltaic pile was set up in England by William Nicholson (1753-1840) and Anthony Carlisle (1768-1840). To ensure contact between the end plates and the moist material between the different pairs, the two experimenters placed a few drops of water on the top plate, and then made the circuit complete. They were surprised to observe a continuous stream of bubbles given off from the water; and at once proceeded to examine the effect on a larger scale.[1] The circuit was completed by dipping gold wire connected to the end plates of the pile in a vessel of water. In this way it was found that hydrogen and oxygen were given off at the points where the wires entered the water. This experiment, performed in London on the 2nd of May 1800, was the first in which water was electrolytically decomposed. Cavendish had previously synthesized water by exploding a suitable mixture of hydrogen and oxygen in his eudiometer. Here was the reverse effect; the analysis of water by an electric current.

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[1] *Nicholson's Journal*, iv. 1800, p. 179. Also *Phil. Mag.* 1800, vii., p. 337.

Immediately the chemists began collecting pieces of copper and zinc and constructing their own voltaic piles. Now Nicholson and Carlisle had noticed that when brass or copper wire were joined to the extremities of the pile and the circuit completed through a tube of water, hydrogen was obtained at one terminal, but no gas could be collected at the other. When gold or platinum wires were used, however, oxygen appeared at one terminal and hydrogen at the other. A discoloration of the brass wire suggested that oxidation had occurred, and this led them to look for signs of oxidation on the plates of the pile itself. The pile used in one of their experiments consisted of thirty-six half-crowns and an equal number of zinc discs of the same size with wet cardboard between them. After the pile had been in use for some days they noticed that the zinc plates had become oxidised and required frequent scraping and cleaning. These practical considerations led not only to improvements in the construction of the voltaic pile, but also to investigations of the chemical decompositions brought about by them. Hence arose a chemical theory of the pile. It was supposed that the oxidation of the zinc and the accompanying changes are in some way the cause of the electrical phenomena exhibited.

Now Volta himself proposed a purely electrical theory of the pile, the so-called *Contact Theory*. In a letter to Sir Joseph Banks,[1] Volta describes how he found that the plates of his pile showed signs of electrification before the circuit was completed. He described how a shock can be felt when the extreme plates of the pile (of 40 plates) are touched simultaneously with the two hands, and compared the effect as of about the same intensity as a feebly charged Leyden jar, or as that of ' a torpedo in a languishing state.' He also pointed out that when a copper and zinc plate, each held by means of insulating handles, are made to touch one another, and then separated and brought near a delicate electroscope, the divergence of the leaves shows that the metal discs are electrified. Volta's electroscope consisted of gold leaves supported by straws, and was an improvement on the pith ball variety used by Cavendish. Volta goes on to say in his letter that he considers the phenomena of the pile to be due to the contact of the different metals with the moist conductor. He mentions that the pile is better if salt water is used to moisten the pasteboard between the plates, and says that the electrical force of the pile is apparently inexhaustible. He says:

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[1] *Phil. Trans.* 1800, p. 403 : ' On the Electricity excited by mere Contact of Conducting Substances of different kinds.'

> 'This endless circulation of the electric fluid may appear paradoxical or even inexplicable, but it is none the less real. . . . I found myself obliged to combat the pretended animal electricity of Galvani, and to declare it an external electricity moved by the mutual contact of metals of different kinds.'[1]

Volta goes on to discuss possible effects of the electricity from a pile on the senses of sight and hearing. He concludes by saying, 'there will here be much to occupy the anatomist, the physiologist and the practitioner.'

§ 4. *Humphry Davy*

The chemical as distinguished from the contact theory of the pile was supported by Humphry Davy (1778-1829). He was born at Penzance, and afterwards articled to a surgeon-apothecary of the town. Davy intended to follow the medical profession, and with that aim he accepted the offer of an assistantship under Dr. Beddoes of Bristol. Now this Dr. Beddoes was the founder and director of a curious institution intended for the treatment of various ailments by the administration of gases. It was called the 'Pneumatic Institution.' Here Davy found a well-equipped laboratory and many opportunities for experimenting with gases, and it was not long before he succeeded in isolating a new gas, nitrous oxide, known as 'laughing gas.'

Soon afterwards Count Rumford, who was requiring a chemical instructor for the recently established Royal Institution, invited Davy to come as lecturer and director of the laboratory. Davy accepted the offer, and two years later was appointed professor. His lectures at the Royal Institution were attended by large

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[1] *Phil. Trans.* 1800, pp. 421, 423.

HUMPHRY DAVY.

gatherings of fashionable and well-known people. His fame increased year by year, and reached its height when in 1812 he was knighted by the Prince Regent. Davy married a wealthy widow, and travelled for some time on the Continent, where he met a number of distinguished men of science. On his return to England he invented the miner's safety lamp, which has made his name familiar throughout the world.

Soon after Davy's appointment at the Royal Institution, the interest of the world was centred on the phenomena of the voltaic pile, and Davy himself made some important investigations on electrolytic decomposition. At first he ascribed the electrical effects produced by the pile to the chemical changes going on in it, the chief of these chemical changes being the oxidation of the zinc. Davy designed modified forms of the voltaic pile, using different pairs of metals with different conducting liquids between them.

Davy's chemical theory was supported by his friend, William Wollaston (1766-1828), who himself made important contributions to physical knowledge. Wollaston cited a number of experiments which he thought proved that the primary cause of the voltaic current is the oxidation of the metals.

> 'We know,' said Wollaston, 'that when water is placed in a circuit of conductors of electricity, between the two extremities of the pile, if the power is sufficient to oxidate one of the wires of communication, the wire connected with the opposite extremity affords hydrogen gas. . . . It would appear that the formation of hydrogen gas depends on a transition of electricity between the fluids and the metal. . . . We see, moreover, in the first experiment that the zinc without contact of any metal has the power of decomposing water ; and we have no reason to suppose that the contact of the silver produces any new power, but it serves merely as a conductor of electricity, and thereby occasions the formation of hydrogen gas.' [1]

In 1806 Davy put forward fresh views on the theory of the pile. Puzzled by small quantities of alkali that appeared during certain cases of electrolysis, he took extreme precautions to exclude any extraneous chemical substances from the water and to prevent any from being dissolved from the containing vessel. His error had, in fact, come from contamination of his terminals and vessels. He now employed gold wire terminals and agate cups, and obtained no trace of alkali or other impurity. He therefore concluded that perfectly pure water is decomposed by a current into oxygen and hydrogen only. Davy seems to have had the conception of the electrical energy of the cell being derived from its chemical changes. The doctrine of the conservation of energy was as yet, however, not explicit.

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[1] *Phil. Trans.* 1801, p. 427.

> 'The great tendency,' says Davy, 'of the attraction of the different chemical agents, by the positive and negative surfaces in the voltaic apparatus, seems to be to restore the electrical equilibrium.... The electrical energies of the metals with regard to each other, or the substances dissolved in the water, in the Voltaic and other analogous instruments, seem to be the causes that disturb the equilibrium, and the chemical changes the causes which tend to restore the equilibrium; and the phenomena most probably depend on their joint agency. In the Voltaic pile of zinc, copper and solution of muriate of soda, in what has been called its condition of electrical tension, the communicating plates of copper and zinc are in opposite electrical states. And with regard to electricities of such very low intensity, water is an insulating body: every copper plate consequently produces by induction, an increase of positive electricity upon the zinc plate; and every zinc plate an increase of negative electricity on the opposite copper plate.... When a communication is made between the two extreme points, the opposite electricities tend to annihilate each other, and if the fluid medium could be a substance incapable of decomposition, the equilibrium ... would be restored. But solution of muriate of soda being composed of two series of elements possessing opposite electrical energies, the oxygen and the acid are attracted by the zinc, and the hydrogen and the alkali by the copper. The balance of power is momentary only, for solution of zinc is formed, and the hydrogen disengaged. The negative energy of the copper and the positive energy of the zinc are consequently again exerted ... and the process of electromotion continues as long as the chemical charges are capable of being carried on.'[1]

Davy's investigations of the effect of the passage of a Voltaic current through pure water and also through different solutions led him to try the effect of passing a current through other substances. Accordingly, he melted pure caustic potash in a platinum spoon, dipped a platinum rod in the fused substance, and connected spoon and rod to a voltaic pile. Bright metallic globules presently appeared. At that time potash was regarded as itself an element; now a new substance had been obtained from it. Davy named the new metal, potassium, and soon after isolated sodium by similar means.

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[1] *Phil. Trans.* 1807, pp. 1-56.

Davy's theory was extended in his Bakerian Lecture for 1826. *Phil. Trans.* 1826, pp. 383-422. The lecture gives an extremely valuable account of contemporary electrical and chemical theories.

Davy and others observed that when a current passes through a solution, the products of decomposition appear only where the wires from the voltaic pile enter the solution. An ingenious hypothesis to account for this was advanced in 1805 by Theodor von Grothuss (1785-1822),[1] and adopted or independently put forward by Davy[2] in the following year. Grothuss and Davy supposed that the pole exerts an attraction sufficient to break up the particles near it. The pole leading from the copper plate of the pile was thought to repel hydrogen and metals and to attract oxygen and acid substances. This repulsion or attraction, as the case might be, was considered adequate to overcome the chemical affinity of the combined substances and so to split up the compound. Grothuss pictured a chain of decompositions going on. In the case of water, the oxygen from a molecule touching the pole coming from the copper plate of the pile was, he thought, attracted away from the hydrogen with which it was previously combined. The hydrogen atom thus abandoned combined with the oxygen of the adjacent molecule. This left another hydrogen atom free, which in its turn caused the next molecule to split up. Eventually a hydrogen atom was left at the end without an oxygen molecule as mate, and was consequently liberated at the other pole.[3]

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[1] *Annales de Chimie*, 1806, lviii. p. 54.

[2] Bakerian Lecture of 1806, in *Phil. Trans.* 1807, p. 1.

[3] In this chapter we are using the terms atom and molecule with their modern significance: actually the distinction between atoms and molecules was made by Avogadro in 1811 and by Ampère in 1814.

§ 5. *Beginnings of the Ionic Theory*

The hypothesis of Grothuss and Davy held the field until attacked by Auguste de la Rive (1801-1873) of Geneva nearly twenty years later (see p. 141). By that time, however, both physical and chemical knowledge had greatly developed. The subsequent work of Clausius, Hittorf, Kolrausch, Arrhenius and Nernst, resulted in the growth of the *ionic theory*, one of the chemist's most powerful weapons.

It is of great interest to note that an electro-chemical or dualistic theory was put forward as early as 1812 by the great Swedish chemist, Jons Jacob Berzelius (1779-1848). Berzelius maintained that every compound is made up of two parts oppositely electrified, and that chemical combination always results from the union of two oppositely electrified parts or elements. Such a union results in a neutralization of the opposite electrifications and the formation of a stable compound. In some cases he considered that the neutralization was incomplete, the compound retaining either a positive or a negative charge, which would render it capable of further combination. It follows at once, from this conception of electrical charge, that the replacement of one electro-positive atom (let us say) can only be made by another electro-positive atom. According to Berzelius, hydrogen and chlorine are oppositely electrified since they combine with such readiness. Yet it was shown later that chlorine can replace hydrogen in a compound, for example, in the chlorine substitution products of the paraffins.

The theory of Berzelius introduced too much simplification, and became discredited when chemists realised the many exceptions which serve to disprove his rule. But the theory is of great historic interest when we consider modern views of the structure of the atom and the electronic theory of valency. The views of Berzelius at least directed the attention of contemporary chemists and physicists to a link between their respective sciences. It was not long before an important relationship was also found between the hitherto separate sciences of electricity and magnetism. The history of science shows that a clear conception of the end in view is often the surest guide to the attainment of that end. Hypothesis often precedes the observed facts. In 1807 Oersted of Copenhagen announced his intention of trying the effect of electricity on a magnetic needle, and after some years his work met with success. Oersted had some notion of what he wanted to find, as had his contemporary Dalton who was seeking for atoms when he found them.

IV

ELECTRO-MAGNETISM

§ 1. *Study of Magnetism in the Eighteenth Century*

We may now return to consider the study of magnetic phenomena. Certain new facts were brought to light during the eighteenth century. In 1750 John Michell (see p. 37) published *A Treatise on Artificial Magnets; in which is shown an easy and expeditious method of making them superior to the best natural ones.* In this he describes the attraction of unlike poles and repulsion of like poles as observed by Gilbert. With the aid of a torsion balance, however, Michell was able to make a comparison of the magnetic force at different distances. From the conclusions thus obtained he deduced a law of inverse squares corresponding to the law of force between charged bodies.

Aepinus (see pp. 37-38), who had adopted Franklin's *One Fluid Theory* of Electricity, proposed a similar theory for magnetism. He regarded the poles as regions where a magnetic fluid is in excess of, or less than normal. Afterwards two magnetic fluids, boreal and austral, were postulated in order to interpret magnetic attractions and repulsions. The fact that certain kinds of iron long retain their magnetism was accounted for by supposing that the magnetic fluid becomes entangled within the pores of the material. Thus magnetic and electric fluids must needs differ in their properties, for it had been recognized that a charged body shows electrical effects only on its surface.

Coulomb (see pp. 36-37), like Michell, verified the law of inverse squares for magnetic poles, and carried the Two Fluid Theory a stage further. He had observed that a magnet, when broken however small, shows poles at the broken ends. He therefore supposed that the magnetic fluids are contained within the ultimate particles of magnetic bodies, each small particle containing as much boreal as austral magnetism.[1] This notion of molecular magnetism was developed later by Weber, and also used by Ampère in his treatment of magnetic shells (p. 71).

At the end of the eighteenth century certain similarities between electrical and magnetic phenomena were realized and the law of force had been shown to be the same for each. Yet so far no clear relationship between the two sets of phenomena had emerged. Franklin, it is true, had unsuccessfully attempted to magnetize a sewing-needle during a thunderstorm and also by the discharge from Leyden jars. It was popularly held, too, that knives became magnetized during a thunderstorm, though no one had adequately demonstrated the existence of such a change. In the early years of the nineteenth century the experiment was made of suspending an insulated voltaic pile to see if it should set in any definite direction.[2] No effect, however, was detected. Some years later the question of the connection between electricity and magnetism was taken up by Oersted of Copenhagen (1777-1851).

§ 2. *Oersted's Discovery*

Hans Christian Oersted was born in the little town of Rudkjoking on one of the Danish islands. His father was an apothecary, and the family lived in narrow circumstances. Nevertheless, young Hans and his brother educated themselves so far as they could from books and without the help of teachers. At twelve years old, Hans had to help in his father's shop, and here he took every opportunity of dabbling with chemicals. By dint of much arduous study and frugal living the brothers secured the means to proceed to the University of Copenhagen. Hans studied astronomy, physics and medicine, and also found time to attend lectures on theology and philosophy. It was for a thesis on metaphysics that he obtained his doctor's degree at the early age of twenty-two. The only employment he could find, however, was in an apothecary's shop. While thus engaged he spent his spare time in study, and was soon giving lectures on chemistry and physics.

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[1] *Histoire de l'Académie des Sciences*, 1789, p. 455.

[2] By the French physicists Hachette (1769-1834) and Desormes (1777-1862).

At this time the discoveries of Volta were being announced to the world. All men of science took the keenest interest in the newly-found phenomena. Oersted's attention was aroused, and he began to perform a series of experiments which led to important results. Fortunately he was able to travel for a time and visit the principal cities of the Continent. He assimilated new ideas with great rapidity, and published some important treatises on his return. His brilliant lectures and the publication of his first researches paved the way for his appointment in 1806 to the Chair of Physics at Copenhagen. His new duties and his own investigations occupied his entire time for the next six years, but in 1812-1813 he again travelled, and stayed a considerable time in Berlin and then in Paris. From his publications at the time it is evident in what directions his thoughts were now working. He even expressed an anticipation of the existence of a close connection between electric, galvanic, magnetic and chemical effects.[1] If galvanism be a 'hidden form of electricity' (*i.e.* of static electricity), he thought it probable that magnetism might be another 'hidden form' of it, and he began to ponder ways of observing the effect of galvanism on a magnet.

Not for some years, however, were his hopes realised: meanwhile he continued his work at the university. In one of a course of lectures delivered to advanced students during the winter 1819-20 on Electricity, Galvanism and Magnetism, he held a wire conducting a current over a needle at right angles to the magnet. No effect was observed. After the lecture he tried the experiment again with the wire parallel to the needle (Fig. 21). A distinct movement took place. The procedure was repeated. Still the same thing happened. Here was the result he had been seeking so long. The experiments were carefully confirmed and published in 1820.[1]

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[1] The title of one of his papers published during his sojourn in Paris was *Récherches sur l'identité des forces électriques et chimiques.*

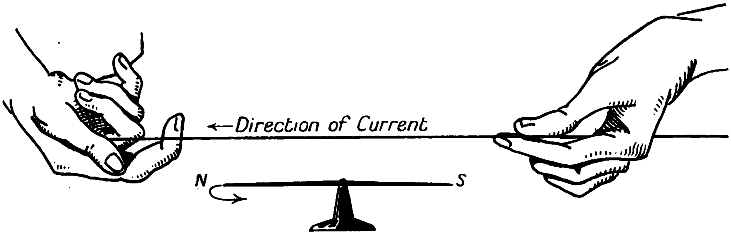

FIG. 21.—OERSTED'S EXPERIMENT.

An account of the discovery contained in a letter from one of Oersted's pupils to Faraday is of such interest that we will give an extract :

> 'Oersted was a man of genius, but he was a very unhappy experimenter ; he could not manipulate instruments. He must always have an assistant or one of his auditors who had easy hands, to arrange the experiment. . . . Already there was a general thought that there was a great conformity and perhaps identity between the electrical and magnetic force ; it was only the question how to demonstrate it by experiments. Oersted tried to place the wire of his galvanic battery at right angles over the magnetic needle, but observed no sensible motion. Once, after the end of his lecture, as he had used a strong galvanic battery in other experiments, he said : "Let us now once, as the battery is in activity, try to place the wire parallel to the needle." As this was made he was quite struck with perplexity to see the needle making a great oscillation. . . . Then he said : "Let us now invert the direction of the current," and the needle deviated in the contrary direction. Thus the discovery was made, and it has been said, not without reason, that he tumbled over it by accident. He had not before any more idea than any other person that the force should be transversal.'[2]

Oersted was indeed no experimentalist, and there is no record of any quantitative investigations dealing with the phenomena he had observed. However, he showed that the region surrounding a wire carrying current is the seat of magnetic effects, or, as we should now say, that there is a magnetic field surrounding a current. He had thus demonstrated for the first time the intimate connection between 'galvanism' and magnetism. Having found the result he had sought for so long, Oersted, always a philosopher at heart, at once began to speculate as to ultimate causes.[1] He thus introduced ideas which no modern man of science would use in discussing physical phenomena. Thus he wrote :

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[1] A reprint is available in Ostwald's *Klassiker der Exakten Wissenschaften*, Leipzig, 1895, Nr. 63.

[2] The letter is quoted in Bence Jones's *Life of Faraday*, vol. ii. p. 395.

> 'To the effect that takes place in the conductor and the surrounding space we shall give the name, the *Conflict of Electricity* . . . the electric conflict acts only on the magnetic particles of matter : it is not confined to the conductor, but dispersed at the same time in the surrounding space.' [2]

This passage is of considerable interest. It shows that Oersted realized that in some way the medium surrounding the conductor plays a part in the production of the result. Faraday, and afterwards the great mathematical physicist, Clerk Maxwell, achieved far-reaching results, which can be traced back to the attention to the medium, rather than the conductor itself.

§ 3. *Immediate Results of Oersted's Experiments. Work of Arago, Biot, and Savart*

The significance of Oersted's discovery was recognized at once by the French Academician, Arago (1786-1853), who heard the news while travelling abroad. On his return to Paris, Arago described the experiments at a meeting of the Academy on September 11th, 1820.[3] Oersted's results acted like a ferment. Almost immediately the problem of the relation between electricity and magnetism was taken up by other investigators. Within a few months tremendous achievements ensued.

Arago himself repeated Oersted's experiments, and found that under certain conditions a current flowing in a wire 'develops

[1] Oersted, *The Soul in Nature*, Munich, 1850, English translation, London, 1852.

[2] Ostwald, *Klassiker der Exackten Wissenschaften*, Nr. 63, p. 7.

[3] 'Experiences sur l'effet du conflict electrique sur l'aiguille aimantée, par M. H. Chr. Oersted,' *Annales de Chimie*, xiv, 1820, p. 417.

the magnetic virtue.' As we should say, it *induces* magnetism in previously unmagnetized iron filings. Arago arranged his apparatus so that the current from a voltaic pile should pass through a cylindrical spiral of fine copper wire. On completing the circuit the iron filings clung to the wire, but on disconnecting the spiral the filings fell off.[1] Arago also noticed that a magnetic needle suspended over a rotating copper disc followed the movements of the disc, although not connected with it directly (Fig. 22). This curious effect became known as the *magnetism of rotation*. No interpretation of the phenomenon was forthcoming until the discovery of electro-magnetic induction by Faraday.

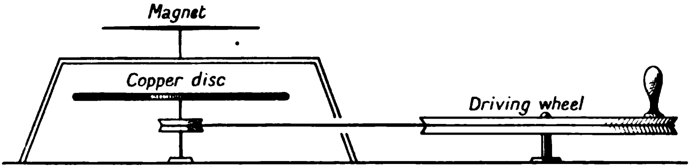

FIG. 22.—ARAGO'S ROTATIONS.

The first quantitative investigations and mathematical treatment of electro-magnetism were made by two other French physicists, Biot (1774-1862) and Savart (1791-1841). At a meeting of the Academy on October 30th, 1820, they announced [2] that they had found experimentally that the force at any point in the neighbourhood of a long straight conductor varies inversely as the distance from that conductor. The relative values of the force at different distances was estimated from the time of oscillation of a small magnet suspended from a fibre of unspun silk. The result, now known as the law of Biot and Savart, formed the basis for their analysis.

Now it had been known from the time of Gilbert that two magnets attract or repel each other, if free to move. It was known, too, that attractions and repulsions take place between electrified bodies. Moreover, Arago had shown that a cylindrical coil of wire carrying current acts like a magnet[1] (Figs. 23, 24). The question which now suggested itself was: Can conductors carrying current attract and repel one another? We must bear in mind that the investigation of such a problem requires specially constructed apparatus, for the current naturally requires

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[1] *Annales de Chimie*, xv, 1820, p. 93.

[2] *Ibid.* xv, 1820, p. 222.

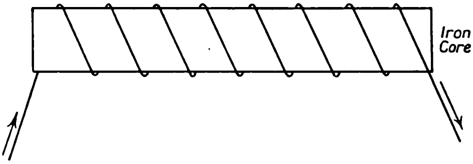

FIG. 23.—SIMPLE ELECTRO-MAGNET.

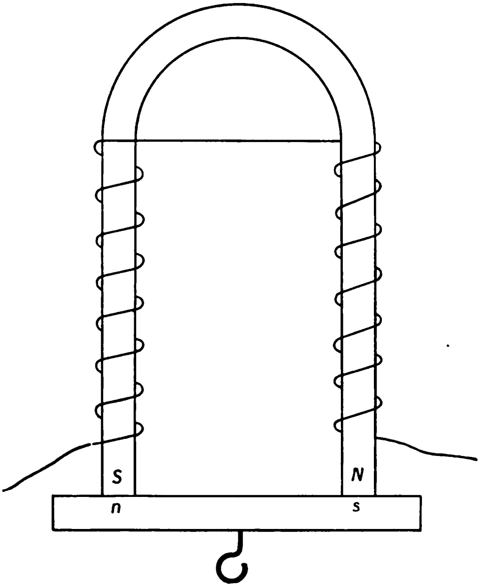

FIG. 24.—HORSE-SHOE ELECTRO-MAGNET.

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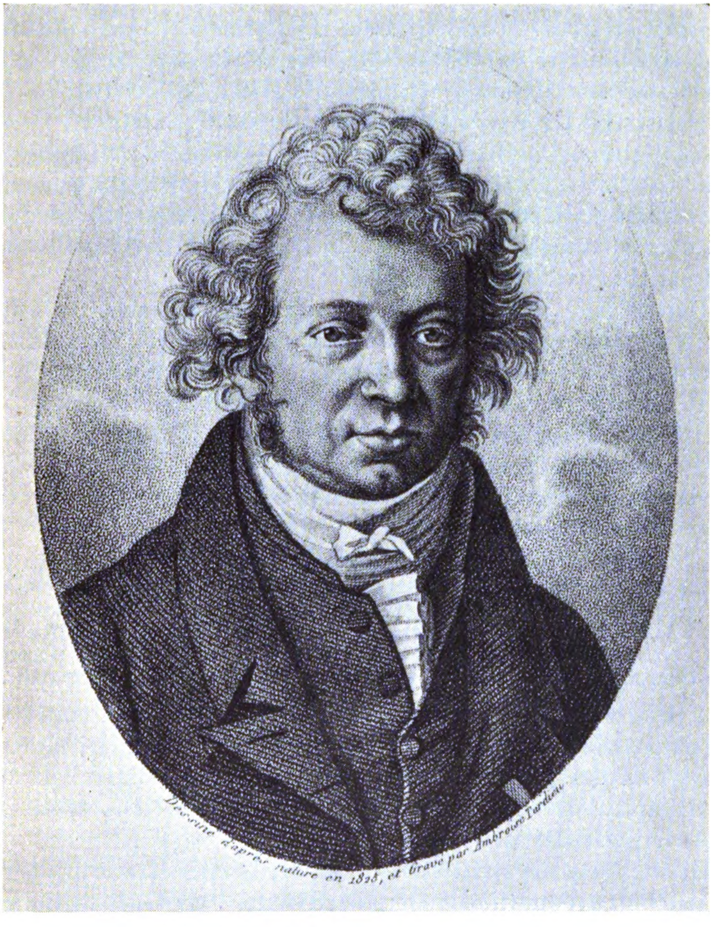
[1] Such a coil when provided with a core of soft iron was afterwards called an electro-magnet. The first large electro-magnet was made in 1825 by William Sturgeon (1783-1850) of London. *Trans. Soc. Arts*, 1825, 43, p. 38.

a complete circuit and part of this must be movable. Nevertheless the question was answered by another French physicist, André Marie Ampère (1775-1836), who, a week after Oersted's discovery, showed that two parallel wires carrying current attract each other if the current is in the same direction and repel each other if the current is in different directions. This was but one of a number of important contributions to what we now call the subject of electro-magnetism. But before trying to appreciate Ampère's work, we may digress for a moment to consider his early life.

§ 4. *Ampère*

André Marie Ampère was the son of a merchant of Lyons. From childhood he seems to have been sensitive, impressionable, yet very lovable. He showed signs of great mathematical ability at a tender age, for when only twelve he demanded to study the works of Euler and Lagrange ! When he was eighteen his father died under tragic circumstances. Lyons had risen in rebellion against the cruel rule of the Jacobins, and for some sixty days held out against the army. Jean Jacques Ampère, the father of André, was Justice of the Peace. When the revolutionary army captured the town, the elder Ampère was condemned to death and executed. Following these events André suffered a prolonged breakdown. Though of cultivated tastes Ampère was very poor, for he had no assured position and could obtain but modest fees for the lessons he gave. Yet he made up his mind to follow a scientific career, and therefore worked every possible moment, often studying before sunrise either alone or with a group of fellow-students. His enthusiasm was in itself an earnest of future greatness.

After a continual struggle against poverty and the death of an ailing wife, he at last obtained a lectureship at Bourg, some distance from Lyons. The appointment carried with it a small fixed salary. While at Bourg, Ampère lectured on physics and pursued his own researches as much as possible. Although his later achievements were in mathematical physics, yet during his


Dessiné d'après nature en 1825, et Gravé par Ambroise Tardieu

André Marie Ampère.

early years he experimented on electrical machines and assisted with the chemical experiments that were in progress at the college. After months of strenuous work, Ampère's results received recognition from the authorities of the Lyceum at Lyons, and he was appointed to a professorship there.[1] In 1805 Ampère was appointed as a lecturer in mathematics at the *École Polytechnique* at Paris. He left Lyons and took up his new life in Paris. Here, despite arduous professional duties, he plunged into all kinds of other intellectual activities. He published six important memoirs on various mathematical subjects, and spent much time pondering over metaphysical problems. In 1809 he obtained a professorship at the *École Polytechnique.*

During these years in Paris, Ampère gathered much material for a treatise on the classification of the sciences. There is no doubt, however, that certain ideas on electricity and magnetism were also then working in his mind, for when he was at Bourg he had heard of the offer of a prize for research in electricity, and had definitely expressed his desire to compete. The prize was offered by Napoleon, and the wording of the notice given in the *Moniteur* is of great interest :

> ' I wish to give as an encouragement a sum of 60,000 francs to the one who by his experiments and discoveries in galvanism and electricity will make a step forward comparable to that made in these sciences by Franklin and Volta, my particular aim being to encourage and direct the attention of physicists to that branch of the science which is, in my opinion, the path to great discoveries.'

The prize was won, in fact, by Davy for his work on electrolytic decomposition, to which we referred in the preceding chapter. Davy's results were published some years before Ampère had an opportunity of experimenting on the subject. His interest, however, was stirred by this event.

During the years spent at Paris, Ampère's mathematical papers gained him a reputation among the savants. His teaching duties being now lighter, he had more time to give to his own investigations. His early mathematical studies had no doubt helped to develop his habit of clear, exact thinking. His study of philosophy had taught him the possibilities and limitations of physical science. He was still, in fact, engrossed in philosophical problems when an event occurred which for a time turned his thoughts into an entirely different channel—the discovery by Oersted of the action of a current on a magnetic needle. Immediately Ampère gave all his attention to the new phenomenon. Soon he was able not only to extend Oersted's experiments, but to give to the world a comprehensive theory which earned for him the title 'The Newton of Electricity.'[1]

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[1] An account of Ampère's life is given by Saint-Beuve in an introduction to the second part of Ampère's *Essai sur la Philosophie des Sciences,* published in 1843 after his death. See also *Journal and Early Correspondence of André Marie Ampère,* edited by Mme. H. C.

§ 5. *The Researches of Ampère*

At a meeting of the French Academy on September 18th, just a week after the announcement of Oersted's results, Ampère described the first of his experiments on the mutual action of currents. Within a week he thus not only devised and made suitable apparatus, but established definite results.[2] In considering Ampère's work we must bear in mind that, when he wrote, no conception of electromotive force or difference of potential was generally recognized. Ohm had not yet given to the world his well-known law, and, in fact, the phenomena of current electricity were still scientific novelties.

Ampère began by distinguishing between what he calls *courant électrique* and *tension électrique*. He pointed out that electrical tension can exist between charged bodies separated by a non-conductor, and that tension also acts between the poles of a voltaic cell before they are connected by a conductor. He then explains that certain phenomena of current electricity are quite different from the effects shown by charged bodies. Notably he observed that, whereas in the case of charged bodies, unlike charges attract and like charges repel each other, the opposite is the case with electric currents, for two parallel portions of a circuit are mutually attracted if the currents are in the same and mutually repelled if the currents are in the opposite direction. Ampère then proceeds to describe the apparatus by which he established his results (Figs. 25, 26).

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[1] Given him by Clerk Maxwell some fifty years later.

[2] *Annales de Chimie*, xv, p. 59.

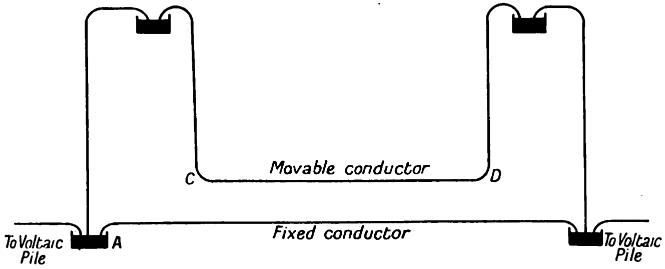

FIG. 25.—AMPÈRE'S APPARATUS I.

Fig. 25 shows a circuit divided in such a way that the portion *CD* is movable while *AB* is fixed. The ends of the movable framework dip into mercury cups by which the current is led away. The whole apparatus is enclosed in a glass case to avoid disturbing air currents. As soon as the circuit is complete with

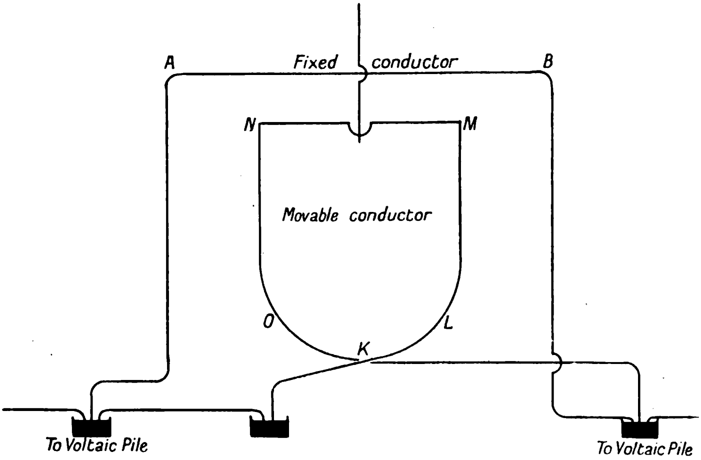

FIG. 26.—AMPÈRE'S SECOND EXPERIMENT.

the current flowing in the same sense along *AB* and *CD*, the movable part is attracted. Fig. 26 shows another arrangement of a movable conductor *NMLO* and a fixed conductor *AB*. Fig. 27 gives an ingenious arrangement of coils wound round glass tubes. The ends of the wire dip into mercury cups at *M* and *N*, which are connected to the extremities of a voltaic pile.

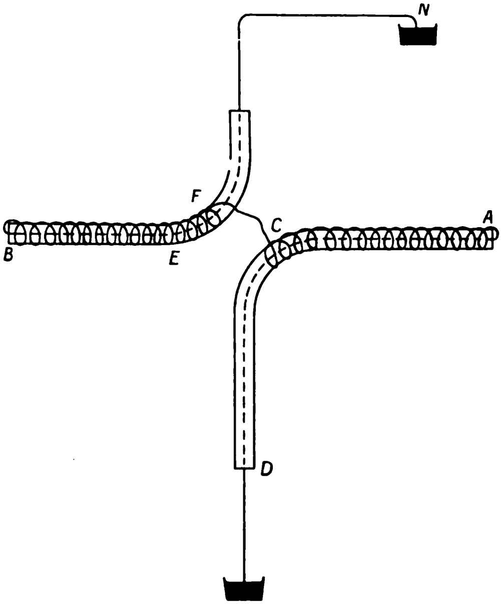

FIG. 27.—APPARATUS SHOWING ACTION OF HELICAL CURRENTS.

The coil *BA* is mounted so as to swing easily. Ampère found that when a current was passed through, it behaved in every way like a magnet suspended in a horizontal plane. Ampère's summary of his results is as follows :[1]

1. Two electric currents attract when they flow parallel to one another in the same sense, and repel when they flow parallel to one another in the opposite sense.

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[1] *Annales de Chimie*, xv, p. 209.

2. It follows that when the metallic conductors along which they flow cannot turn in the parallel plane, each tends to lead the other into a position parallel to it and in the same sense.

3. These attractions and repulsions are absolutely different from the attractions and repulsions of ordinary electricity.

4. All the phenomena discovered by Oersted representing the mutual action of an electric current and a magnet are included in the law of attraction of two electric currents. This law follows from admitting that a magnet is but an assemblage of electric currents produced by the action of the particles of iron on one another, analogous to that of the elements of a voltaic pile.

We will consider Ampère's speculations as to the nature of magnetism later. For the present let us see how he improved upon his first experiments and developed the whole subject along mathematical lines.[1]

Before proceeding to his analysis, Ampère draws attention to two methods of experimentation which may be applied to the mutual action of currents. One consists in the actual measurement of the forces at varying distances: the other consists in balancing the effects produced by two currents so that they both act on some other body and keep it in equilibrium. The second is what we now call a *null method*, and such a method always gives greater accuracy in experimentation. In order to find out when the two effects were truly balanced, he devised an apparatus consisting of two coils mounted so that they were equally and oppositely affected by the earth's magnetism. His apparatus was thus an *astatic* pair of coils (Fig. 28). As such it formed a delicate detector of electro-magnetic effect. Ampère's mathematical treatment rested on four experimental results, which we may summarize as follows:

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[1] *Annales de Chimie*, xx, 1822, p. 398. Mémoire sur la determination de la formule qui représente l'action mutuelle de deux portions infiniment petites de conducteurs voltaiques.

Annales de Chimie, xix, 1825, p. 381. Mémoire sur une nouvelle expérience electrodynamique, sur son application à la formule qui représente l'action mutuelle de deux élémens de conducteurs voltaiques; et sur de nouvelles consequences déduites de cette formule.

1. Two equal currents flowing close together and in opposite directions exactly counterbalance each other.

2. The effect of a current flowing in a conductor twisted and bent into an irregular form is the same as if the wire were straightened out.

3. The force exerted by a closed circuit on an element of another circuit is at right angles to the line uniting them.

4. The force between two current elements is equal and opposite if the dimensions of the coils are proportional to their distances from the point where the effects neutralize each other.

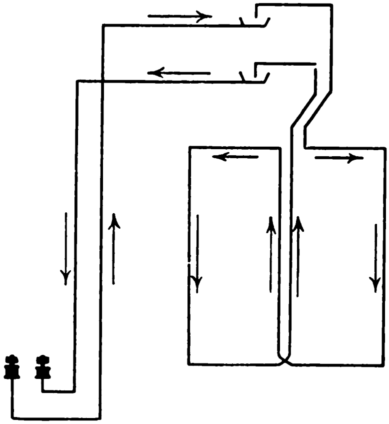

FIG. 28.—AMPÈRE'S ASTATIC BALANCE.

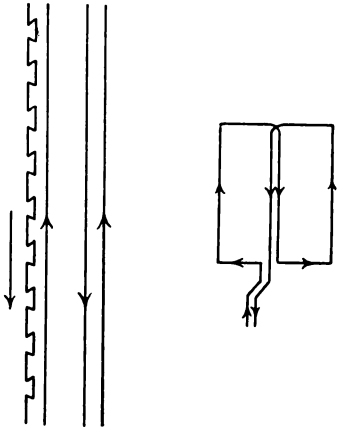

FIG. 29.—AMPÈRE'S EXPERIMENT showing the effect of currents in opposite directions on the astatic balance.

In reaching the first two conclusions Ampère used his astatic balance, which was found to be unaffected when the currents flowed in opposite directions as shown in the diagram (Fig. 29).

In reaching the third conclusion he devised a piece of apparatus in which a conductor was capable of moving only in the direction of its length. The movable conductor was in the form of a circular arc resting between two little troughs of mercury. The current entered at one trough, passed along the arc and left at the other trough. A number of different closed circuits were brought near, but no movement in the direction of its length was detected (Fig. 30).

In reaching his fourth conclusion, Ampère again used the astatic balance. He placed the circuits on either side, the dimensions of the circuit being proportional to their distances from the balance. When this condition was realized, the balance remained in equilibrium, showing that the effects produced by the currents in the two circuits were equal.

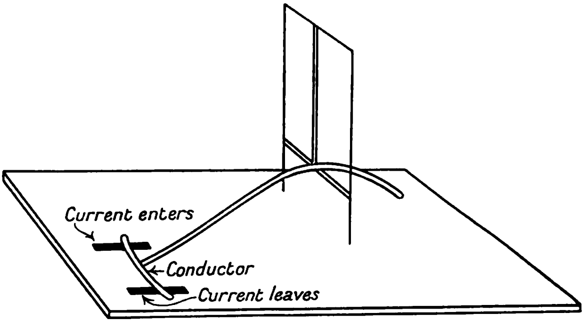

FIG. 30.—AMPÈRE'S APPARATUS
with a conductor capable of moving only in the direction of its length.

Let us now see what can be deduced from these experimental results. We cannot enter into a full discussion of Ampère's mathematical work. It must suffice to indicate the kind of reasoning he adopted. Having obtained a general expression for the force between two current elements, he applied his formula to the special case of two parallel conductors carrying current. He thus obtained a result identical with that previously obtained by Biot and Savart.

Let us take the four experimental results stated above: if ds and ds' be elements of any two circuits, r the distance between them and i and i' the current strengths, from (1) it follows that the force must be proportional to the product of the current strengths or to some odd power of the current strengths. From (2) it follows that the effect of ds on ds' must be the vector sum of the components of ds on ds'. From (3) the resolved part of the force along the direction of ds' must vanish when summed for the whole circuit. Calling the required force F we may write as the simplest form for F,

$$F = ii'\,ds\,ds'\,f(r),$$

where $f(r)$ is some function to be determined. From (4) we can find this function as follows:

Let us denote the circuits in Ampère's fourth experiment by A and C and the balance by B. Then if the dimensions of C are n times those of B and the dimensions of A are $1/n$th those of B, the distance of C from B must be n times that of A from B (Fig. 31). These distances we will denote by nd and d respectively. Denote the current strengths in these circuits by a, b, c respectively, and the lengths of corresponding elements by A_1, B_1, C_1 and A_2, B_2, C_2. We may say that the force F between B_1 and A_2 is proportional to the current strengths, to the lengths of the elements and to some undetermined function of the distance, *i.e.*

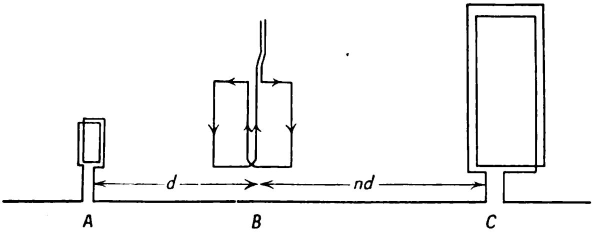

FIG. 31.—AMPÈRE'S APPARATUS for testing the simultaneous effect of two circuits on the astatic balance.

$$F = abB_1A_2f(d).$$

Similarly the force F^1 between C_1 and B_2 may be written

$$F^1 = cbC_1B_2f(nd).$$

But we are given that $C_1 = nB_1$

and $B_2 = nA_2$;

hence $n^2B_1A_2 = C_1B_2$.

But the same current was passed through the coils A and C, hence $a = c$; $\therefore$ we may write

$$F^1 = abn^2B_1A_2f(nd).$$

Now by experiment $F = F^1$; $\therefore$ equating the two expressions we have

$$abB_1A_2f(d) = abn^2B_1A_2f(nd),$$

i.e. $f(d) = n^2f(nd)$.

Clearly this is true only if the function is that of the inverse square.[1] Hence the simplest form of the expression giving the action of current on current is

$$F=\frac{ii'\,ds\,ds'}{r^2},$$

the integration depending, for special cases, of course, on the kind of circuits employed.

We may apply Ampère's reasoning to a determination of the intensity of the force at a point on the axis of a circular coil carrying current (Fig. 32). The force due to an element ds is at right angles to the line joining the point P to the element. The resolved part of the force in the direction of the axis is

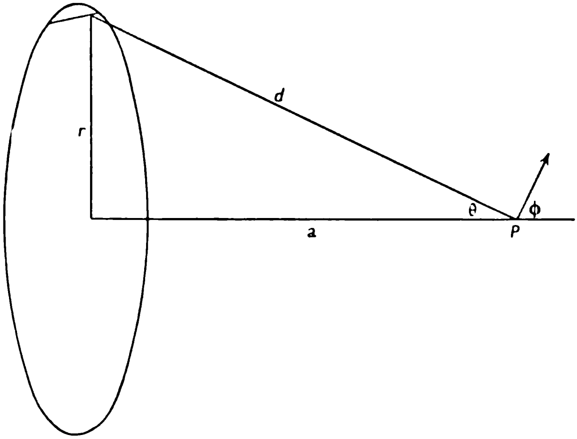

FIG. 32.—FORCE AT A POINT ON THE AXIS OF A CIRCULAR COIL.

$$dF=\frac{i\,ds}{d^2}\cos\phi.$$

From the geometry of the figure,

$$\cos\phi=\sin\theta=\frac{r}{d};$$

$$\therefore\ dF=\frac{i\,ds}{d^2}\frac{r}{d},$$

---

[1] This proof is a slightly modified form of the one given in Clerk Maxwell's *Treatise on Electricity and Magnetism*, vol. ii, 3rd edition, Oxford, 1892, p. 163.

$$F=\int\frac{i\,ds}{d^2}\frac{r}{d},$$

i.e.
$$F=\frac{i\,2\pi r^2}{d^3}.$$

When the point P is at the centre of the coil the expression reduces to
$$F=\frac{2\pi i}{r},$$

which is the well-known formula used in the theory of the tangent galvanometer (see p. 116).

As a mathematician, Ampère sought to interpret all physical phenomena in terms of equal and oppositely directed forces between the particles of bodies. In connection with his study of electro-magnetism, however, he offered certain suggestions as to the ether in order to explain the actions he had observed. Thus he suggested that the forces between currents may be due to reactions of the ether set up by the currents, reminding one of the ether-strain hypothesis of the later nineteenth century. He suggested that the electric current itself is the result of certain interchanges of the electric fluids taking place between the molecules of the substance constituting the conductor. Ampère developed the theory of the equivalence of magnets with wires carrying currents. He did this by showing that an electric current is equivalent, as to its magnetic effects, to an extremely thin sheet of magnetic material which he called a *magnetic shell.* Certainly the magnetic effects of a coil carrying current are just as if the coil had a north face and a south face : two magnetic shells would attract or repel one another, and would exert a force on a small magnet at right angles to their plane.

The conception of the magnetic shell proved a very useful one for Ampère and for subsequent investigators. The results that he deduced by its aid agreed with the quantitative results of Biot and Savart to which we have referred. Nevertheless, Ampère considered the fundamental entity to be not magnetism, but electricity. He supposed that a current flows round each molecule of a magnetic body, the currents in adjacent molecules neutralizing each other and the material behaving as if the magnetism were concentrated at the poles. This conception is analogous to the molecular theory of Weber (see p. 124).

In the case of an extremely thin piece of magnetic material, all the molecular currents except those on the boundary neutralize each other. Hence the equivalence of a current in a coil with a magnetic shell (Fig. 33). It is interesting to note that Ampère's conception of a current flowing round each molecule anticipated to some extent the more modern conception of the atom, the revolving electrons constituting the current.

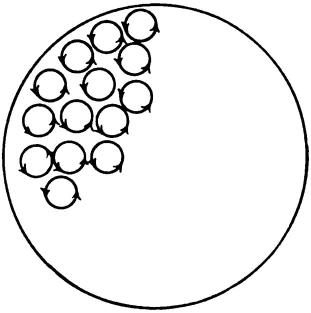

FIG. 33.—MOLECULAR CURRENTS IN A MAGNETIC SHELL.

An ingenious little rule for determining the direction in which a current is flowing was devised by Ampère. Suppose a man to be swimming in the direction of the current, so that the current enters at his feet and leaves at his head, then if he is facing a magnetic needle, the north pole will be deflected towards his left hand (Fig. 34). Ampère's name has been applied to the practical unit of current, and is therefore familiar to every working electrician who talks of ' amps ' and ' amperage.' It is of interest to

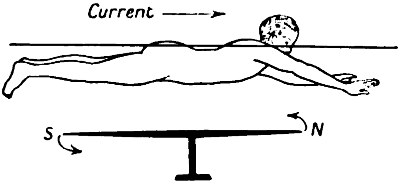

FIG. 34.—AMPÈRE'S SWIMMER.

note that the electric telegraph was first suggested by Ampère, for in 1821 he pointed out that a galvanometer placed at a distant point of a circuit might serve for the transmission of signals.

Neither the theoretical nor the experimental results of Ampère were received favourably at first. It was thought his ideas were opposed to those of Newton, according to whom all forces act in straight lines and not in circles. It is evident that the mathematical part of his writings was little read by his contemporaries. Had his work been adequately studied it would have been seen that the action in straight lines was a primary assumption for the whole of the theoretical side. Probably his critics were confused because he had shown a magnet to be moved circularly ***round a current***, for, as we should now say, the lines of force in the neighbourhood of a straight wire carrying current are concentric circles. Finally, however, the eminent mathematician Fourier (1768-1830) accepted Ampère's results. A little later Laplace (1749-1827), one of the greatest mathematicians of all time, was convinced. Soon, others followed the example of these great mathematical thinkers, and the new views on Electromagnetism became established.

During the later years of his life, Ampère returned to his beloved philosophy and completed his treatise on the scope and classification of the sciences. Homage was paid to him from many countries, and his work received general recognition.

§ 6. *Galvanometers*

Oersted's discovery provided a means for the detection of a current by its magnetic effect. Instruments based on such an action are called *galvanometers*. The simplest type of galvanometer consists of a single turn of wire with a compass needle mounted at its centre. The instrument is adjusted so that the plane of the coil is in the magnetic meridian. When a current is passed through the coil, the magnetic field due to the current tends to turn the needle at right angles to its former direction. The magnetic field of the earth, however, tends to keep the needle in its original position. The needle takes up a position of equilibrium depending on the relative strengths of these opposing fields. Now in every galvanometer there is the *deflecting* force due to the current and a *controlling* force tending to keep the magnet in its original position. To render a galvanometer more sensitive we may

(1) increase the effective action of the current, or

(2) decrease the control due to the earth.

The first method was adopted by the German physicist Schweigger (1779-1857). He devised in 1821 a *Multiplier* consisting of a rectangular framework wound with many turns of wire. The magnet was supported at the centre (Fig. 35). The second method was used by the Italian physicist Nobili (1784-1835). This experimenter took two magnets of nearly

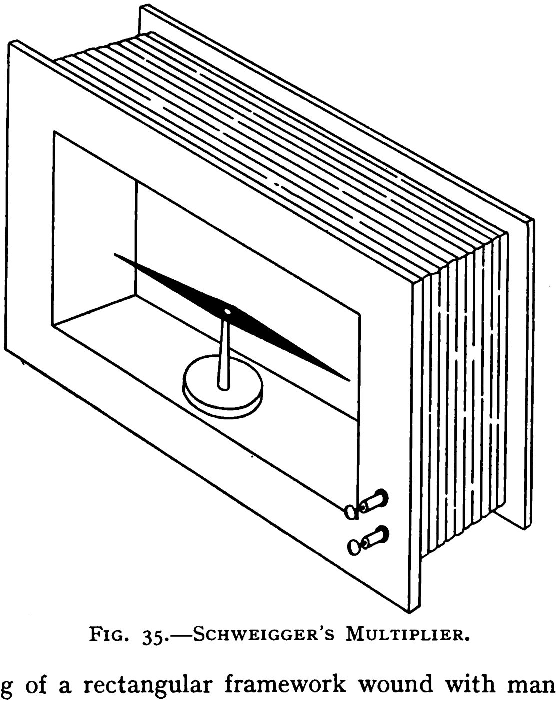

FIG. 35.—SCHWEIGGER'S MULTIPLIER.

equal strength and fixed them to a copper connecting strip so that the poles were in opposite directions (Fig. 36). The pair of magnetic needles were then supported by a fine silk thread, and a coil of wire forming a multiplier made to surround the lower needle only. Since the poles were in opposite directions and the magnets nearly of equal strengths, the action of the earth was almost equal and opposite. The control of the earth was thus reduced to a very small amount, and the pair of magnets was therefore said to be *astatic*. For many years the *astatic galvanometer* was the only sensitive instrument available for the detection of currents.

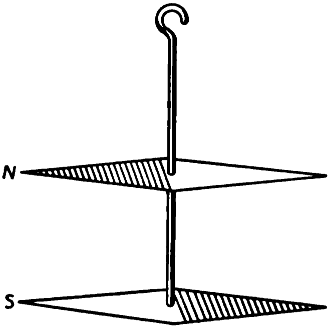

FIG. 36.—ARRANGEMENT OF TWO MAGNETS TO FORM AN ASTATIC PAIR.

§ 7. *Further Developments in the Study of Electricity*

During the years of Ampère's achievements important contributions were also made by other investigators in other lands. Soon after the announcement of Oersted's discovery, a hitherto unexpected relationship between electricity and heat was found by Thomas Johann Seebeck (1770-1831) of Berlin. Seebeck made a circuit consisting of two different metals, copper and bismuth, soldered together. When the junctions were maintained at different temperatures he observed that a current traversed the circuit. Such currents are now known as thermoelectric currents. With a single pair of metals the effect is very slight, but by having a large number of pairs the current can be multiplied. A number of pairs suitably arranged together are employed in the instrument, which is now known as a *thermopile* and used as a delicate detector of radiation.

It had long been known that some substances are better conductors of electricity than others. Thus we have seen how

Cavendish compared the conductivities of different materials, though this part of his work was not known to his contemporaries. Davy, whose services to physics are perhaps insufficiently recognized,[1] carried out some important experiments on the conductivity of different substances. The method used depended on the fact that water could not be decomposed under all circumstances. Davy had observed this in his early researches on electrolytic decomposition. He could not account for the fact, for it must be remembered that although Davy and other experimenters spoke of the *tension* of the pile, the conception of potential difference or electromotive force had not yet clearly emerged.

Davy connected the terminals of a voltaic pile[2] by two conducting paths, one of water in a suitable vessel, and the other of a metal wire. The length of the wire was so adjusted that the water ceased to be decomposed. He then repeated the experiment with wires of different materials and calibres, using always the same vessel of water for the second conducting path. By comparing the results he reached the conclusion that the conducting power of a uniform wire of any particular material depends directly on the area of its cross-section and inversely on the length. He observed that the shape of the cross-section was without significance, the area being the important factor.

§ 8. *The Work of Ohm*

It is unfortunate that Davy did not extend his researches further, for he approached very near to the conceptions of resistance and electromotive force given to the world a few years later by Georg Simon Ohm (1787-1854). Oddly enough, although Ohm did perform a considerable number of experiments, the fundamental law enunciated by him and always associated with his name was the outcome of theoretical deductions. Ohm's great work is a mathematical treatment of the galvanic circuit[1] based on an analogy between the flow of heat and the flow of electricity. In 1822 the theory of heat conduction had been treated fully by Fourier in a work which created widespread interest among the mathematical physicists of the day.[2]

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[1] At about the time of Arago's experiments on electro-magnetism, Davy sent a communication to Wollaston entitled *On the magnetic phenomena produced by electricity*. The paper was read before the Royal Society, November 16th, 1820. Davy, after describing the work of Oersted, cites a number of his own experiments, which he says may or may not have been devised by others. Indeed events moved so rapidly during the autumn of 1820 that it is not always possible to decide priority of claim.

[2] *Phil. Trans.* 1821, p. 433.

Fourier's equation is as follows:

$$\lambda\left(\frac{\partial^2\theta}{\partial x^2}+\frac{\partial^2\theta}{\partial y^2}+\frac{\partial^2\theta}{\partial z^2}\right)=\rho c\frac{d\theta}{dt}$$

where λ is the conductivity and where θ is the temperature, so that $\frac{d\theta}{dt}$ is the rate of change of temperature, ρ the density and c the specific heat, and x, y, z the coordinates of any point. The equation is a general one giving the conductivity in terms of the temperature gradients and rate of change of temperature.

Ohm sought, in electrical conduction, something akin to the *temperature gradient* of Fourier's equations. He begins by considering in a qualitative way how the flow of electricity takes place. He pictures to himself a homogeneous ring of material, of the same thickness throughout, having at corresponding points the same *electrical tension.* This tension Ohm conceives as an inequality in the electrical states of two surfaces situated close to each other. He explains that this inequality disturbs the equilibrium so that the electricity will in its endeavour to re-establish itself, if its mobility be confined to the extent of the ring, flow off on both sides; 'the manner of spreading of the electricity is thus determined, but the absolute force of the electricity at various parts of the ring remains uncertain.' Ohm therefore pictures the ring opened out into a straight line, and represents the absolute force graphically by an ordinate. He assumes that this force diminishes regularly with the distance. He thus arrives at the notion of a gradient analogous to the temperature gradient of Fourier.

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[1] *Die Galvanische Kette mathematisch bearbeitet,* Berlin, 1827. It is a book of some 250 8vo pages. There is an English translation in Richard Taylor's *Scientific Memoirs,* vol. ii. p. 401.

[2] *Théorie Analytique de la Chaleur,* 1822.

After considering the general case of conduction along a body of any shape, Ohm discusses the special case of a long conductor of uniform cross-section which he calls a ' prismatic body.' He says that ' the force of the current in a galvanic circuit is directly as the sum of all the tensions and inversely as the entire reduced length of the circuit. . . . By reduced length is understood the sum of all the quotients obtained by dividing the actual lengths corresponding to the homogeneous parts by the product of the corresponding conductibilities of the sections.'

The simple case of a long conductor of uniform section, he expresses by the equation

$$S=\omega\psi\frac{du}{dx}$$

Where S=magnitude of the current,
ω=section of the material,
ψ=power of conduction,
u=electroscopic force at that point of the conductor whose abscissa is x.

Translating these expressions into present-day terms, we obtain the relationship familiar to all students of elementary physics. If l be the length of the conductor, E the potential difference between the ends, ρ the specific resistance, R the resistance of the wire, and I the current, we have

$$\psi=\frac{1}{\rho}$$

$$R=\rho\frac{l}{\omega}$$

Potential gradient, $$\frac{du}{dx}=\frac{E}{l}$$

Hence the formula, $$S=\omega\psi\frac{du}{dx}$$

may be written $$S=\frac{\omega}{\rho}\cdot\frac{E}{l}$$

$$=\frac{E}{R}$$

or denoting the current by the usual symbol I we have

$$I=\frac{E}{R}$$

Ohm finally gathered up his views and theoretical deductions into a theory of the galvanic circuit. This we may summarize as follows:

(*a*) In a closed voltaic circuit, whatever the form of the conductor, the same quantity of electricity passes across each section perpendicular to the direction of the current.

(*b*) Whatever change is made in one part of the circuit affects the entire action of the pile.

(*c*) The current is in the direct ratio of the electromotive force and in inverse ratio to the resistance.

(*d*) The resistances are composed of:

- (i) The resistance of the solid conductor or connecting wire.
- (ii) The resistance of the liquid conductor. This latter resistance varies owing to continuous chemical changes which gradually reduce the electrical tension.

(*e*) The electromotive force varies directly as the number of voltaic pairs in the pile.

Ohm seems to have used the term *electromotive* force when considering the driving force of the current as a whole. In his treatment of the flow from one element to the next, however, he frequently speaks of *electroscopic* force, as he does in the formula (p. 78). He seems to have considered this electroscopic force as proportional to the volume-density of electricity at the point in question. For him this volume-density was a conception of the same order as that now called quantity of heat per unit volume when the 'steady state' has been reached in heat conduction in a solid. Ohm's work marked a tremendous advance in the science of electricity. The summary we have given shows that he gave a similar definite meaning to the terms *current* and *resistance* as that which we now employ.

Ohm's Law, as his fundamental relationship has been called, is one of the first results to be learned in the most elementary course on the subject. It is continually used in the laboratory and in the electrical engineer's workshop. Its familiarity makes it difficult for us to realize the state of knowledge before its enunciation. Subsequent verifications of Ohm's results were made, and the three electrical magnitudes of *current*, *electromotive force*, *resistance* and the relation between them is now an established part of electrical theory. Despite their vast importance, it was long before Ohm's results were recognized by his contemporaries. Born in humble circumstances, the son of a locksmith, his life is a long record of a struggle against adverse circumstances. As a boy, Ohm had picked up such mathematics as he could from a student at Erlangen. Later he studied at the local Gymnasium of Erlangen, and then had just three terms at the University. He acted as private tutor for a time, and managed to save sufficient money to complete his college course. After a long period of unemployment, during which he continued his studies, he obtained a teaching post at Cologne. Here he spent nearly ten years, and during this time carried out his experimental work and composed the work on the galvanic circuit that we have just considered. He obtained leave of absence in Berlin to complete and publish his book. On his return to Cologne he had to resign his post owing to the criticism of his work by the educational authorities. For many years he had to give odd lessons to keep himself. Not until more than twenty years after the publication of his work on the galvanic circuit were his merits recognized by his countrymen. Ohm was sixty when his great ambition was realized and he obtained a professorship at Munich, having previously been honoured in England by the award of the Copley Medal by the Royal Society. In 1881 the International Congress on Electric Units in Paris honoured his memory by naming the practical unit of resistance the *ohm*, just as they perpetuated the name of Ampère by naming the practical unit of current after him.

But while Ohm had been working in Germany and Ampère in France, the subject of electro-magnetism had been investigated in England by Davy's assistant, Michael Faraday. His researches led to one of the most far-reaching discoveries in the history of science, that of electro-magnetic induction.

V

THE DISCOVERY OF ELECTRO-MAGNETIC INDUCTION

§ 1. *The Early Life of Faraday*

MICHAEL FARADAY was born at Newington in Surrey on 22nd September, 1791. His father was a blacksmith and his mother the daughter of a farmer. When Michael was five years old the family went to London, where they rented rooms in a mews. The records of his early life are few, and his early education consisted of little more than the rudiments of reading, writing and arithmetic. When thirteen Faraday worked as an errand boy at a bookseller's shop and used to deliver the daily papers, and in later life he always had a kindly word for every newspaper boy he saw. After some time thus spent, Faraday became an apprentice to the bookbinder who owned the shop. Thus he continued for seven years. Placed in this position he had many opportunities for becoming acquainted with books, and in his spare moments he eagerly read any scientific works that came into his hands. In this way he studied Mrs. Marcet's *Conversations on Chemistry* and an article on Electricity in the *Encyclopaedia Britannica*. From these works, he tells us, he gained his first taste for science. Faraday used to spend his pocket-money on material for home-made apparatus. He managed to make a voltaic pile out of halfpennies and discs of zinc with pieces of paper soaked in salt solution between. He lost no opportunity of adding to his scientific knowledge, and he describes his enhancement at attending some popular scientific lectures at the cost of a few pence provided by his brother.

About this time, Faraday kept a note-book which he called his 'Philosophical Miscellany,' consisting of a collection of extracts from scientific books and magazines, and containing a record of the experiments he had tried for himself. Towards the end of his apprenticeship, Faraday attended some of Davy's lectures at the Royal Institution. These made Faraday long to give himself entirely to the pursuit of science. But how was this possible for a poor apprentice? He boldly wrote to the President of the Royal Society, but obtained no answer.

It was with sad misgivings that Faraday, his time of apprenticeship complete, went out into the world as a fully-fledged bookbinder. Difficulties beset him from the first. His employer was unsympathetic, and his hours of duty were so long that he had no leisure for his beloved scientific studies. The atmosphere of business was so distasteful to him that he determined to make another effort to gain scientific employment, however humble. How he carried out his resolve is described in a letter written some years later.

> 'When I was a bookseller's apprentice, I was very fond of experiment and very averse to trade . . . which I thought vicious and selfish. My desire to enter the service of science, which I imagined to make its pursuers amiable and liberal, induced me to take the bold and simple step of writing to Sir Humphry Davy expressing my wishes and a hope that if an opportunity came his way, he would favour my views. At the same time I sent the notes I had taken of his lectures.' [1]

The sincere tone of the letter and the neatly written, clear notes made an impression on Davy, who replied courteously to Faraday and granted him an interview. As a result Faraday was appointed Laboratory Assistant at the Royal Institution, and given two rooms at the top of the house and a salary of 25s. per week. This was the manner in which the man who the world has since acknowledged to be the greatest of experimental philosophers, began his life of devotion and service to science.

§ 2. *Faraday as Davy's Assistant*

Faraday's duties were of a very humble kind. He assisted the lecturers in their demonstrations and kept the apparatus and the laboratory clean and tidy, but he had a fair amount of leisure.

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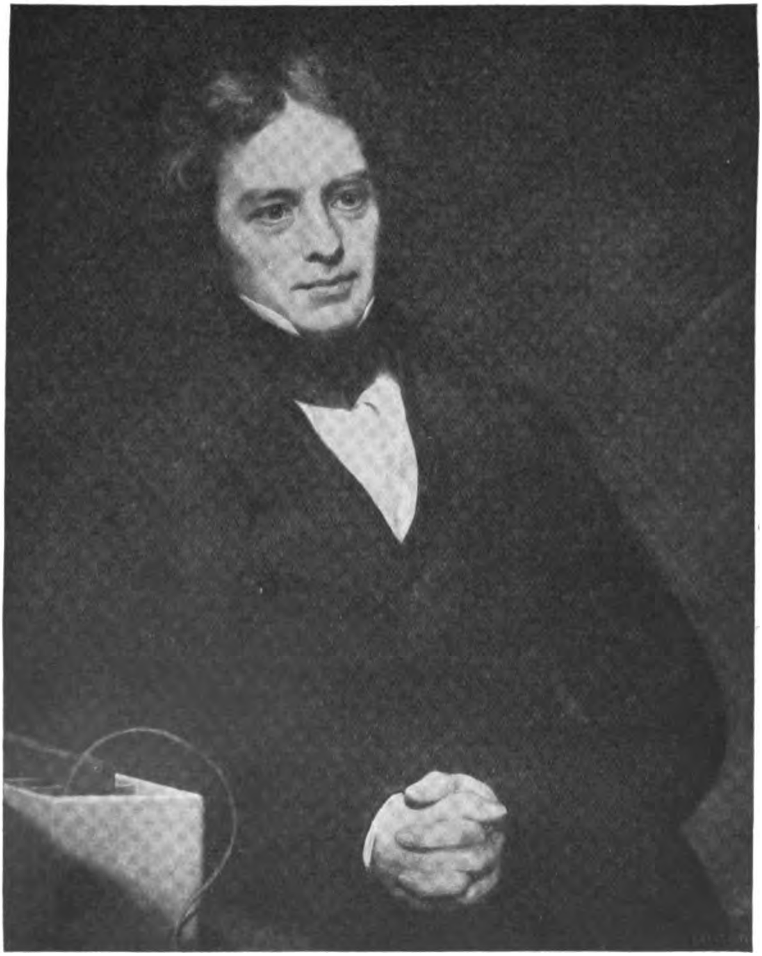
[1] In a letter to Dr. Paris, 1829.



MICHAEL FARADAY.

It was a great opportunity for him that he could observe the details of Davy's experiments, and he sought to grasp the points in his master's investigations. It must be remembered that Faraday had no knowledge of mathematics beyond that of the simplest arithmetic; he had left school at the age of thirteen, and had spent his most impressionable years as a trade apprentice. In fact, he never developed any mathematical facility. It is not surprising, therefore, that a long period of preparation was necessary before his great creative work could be accomplished. But during that time he worked indefatigably, and with the insight of genius saw the possibility of physical truths hitherto undreamed of. Faraday's subordinate position at the Royal Institution rendered him rather isolated, and he often worked for days without guidance. Fortunately, however, he was able to join a scientific club, the members of which were poor men drawn together with the desire for mutual improvement and help. It was at the meetings of this society that Faraday obtained his first experiences in lecturing.

During the autumn of his first year at the Royal Institution, Davy, who by this time had a high opinion of his young assistant, offered Faraday the opportunity of accompanying him abroad and of acting as his 'philosophical assistant.' The offer was gladly accepted, and Faraday was thereby able to visit many of the most important cities of Europe. While at Geneva, Faraday was presented to the distinguished and wealthy Charles de la Rive (1770-1834), the father of the well-known physicist, Auguste de la Rive (1801-1873). The difference in nationality obscured the social barriers that convention would have raised, so that de la Rive accepted Faraday at his face value and remained his steadfast friend.

On his return to England in April 1815, Faraday was promoted to be Assistant and Superintendent of Apparatus at the Royal Institution, and his salary was raised to 30s. per week. Writing of his work at this time, he rejoiced at his 'glorious opportunity of studying chemistry under Sir Humphry Davy.' He speaks, too, of his great love for science. Yet he says in all humility:

'I have learned just enough to perceive my ignorance. The little knowledge I have gained makes me wish to know more.' During the years following his return Faraday was adding to his knowledge of chemistry and physics and gaining skill in the manipulation of apparatus, but he was building up for himself the true principles of all scientific investigations. He was laying sure foundations for the great structure of scientific achievement that has made his name famous throughout the world. In 1816 he published the results of his first original investigation dealing with an analysis of caustic lime. He says:

> 'Sir Humphry Davy gave me the analysis to make as a first attempt in chemistry at a time when my fear was greater than my confidence, and both far greater than my knowledge.... At a time also when I had no thought of ever writing an original paper on science.'

§ 3. *Electro-magnetic Rotations*

During the years immediately following, Faraday's contribution to science was almost entirely confined to chemistry. An important research made during this period on the properties of certain kinds of steel would have been in itself sufficient to have placed him in the front rank of contemporary men of science. But in 1820 a new field of enquiry was opened by Oersted's discovery of the action of a current on a freely suspended magnet. The announcement gave rise to the widest interest in the scientific world. Faraday, like everyone else, was eager to know more of the new discovery. We have seen how successfully the subject of electro-magnetism was taken up by Ampère and other French physicists: and it was not long before Faraday had some important contributions to make. We can picture him in the laboratory of the Royal Institution with magnets and batteries at his disposal. What was more natural than that he should try the experiments for himself? At the request of the editor of the *Annals of Philosophy* he wrote a 'Historical Sketch of Electro-magnetism,' and embodied the results of his own experiments, from which he proceeded to the researches for which his fame is chiefly due.

One day, when Faraday was working in the Laboratory of the Royal Institution, he happened to overhear quite unintentionally a conversation between Davy and his friend Dr. Wollaston. They were discussing the discoveries of Oersted and Arago, and were debating the possibility of making a conductor carrying a current turn round itself, that is, turn on its own axis. Faraday did not see any experiments the friends were trying, but his mind was engrossed with the problems of electro-magnetism, and all his spare time was given to experiments in connection with the historical sketch he was writing. Now Wollaston's plan of making a wire revolve about itself was unsuccessful. But Faraday went to the root of the problem, and so succeeded where Wollaston had failed.

From the experiments of Oersted and from his own verifications of those experiments, Faraday realized that when a current passes through a wire, there is a magnetic force acting transversely to it. He thought that this transverse force might cause a magnet to move round the wire, provided that one end of the magnet was free to move. Since action and reaction are equal, he argued, too, that if a magnetic pole can rotate round a current, a wire carrying current should be able to move round a magnetic pole. Having pictured the experiment in his mind, Faraday then gave his whole attention to practical details. He saw that it was only a question of arranging the apparatus so that in one case the magnet could move, and in the other case, the conductor. He succeeded in producing two simultaneous rotations in the following way:

A circuit consisting of two vessels containing mercury and suitable connecting wires was arranged so that in one vessel there was a fixed magnet and a wire free to rotate, and in the other a fixed wire and a movable magnet (Fig. 37). The current passes from the wire through the mercury in the left-hand cup to a copper pin running into the base of the vessel. The magnet in this cup was fastened to the copper pin by a thread. In the right-hand vessel, the fixed magnet was placed in a socket in the stem of the vessel, and the wire *B* which dipped into the mercury was able to move freely by means of a ball and socket connection at *C*. As soon as the circuit was completed, the magnet in the first vessel and the wire in the second commenced to rotate, and continued so long as the current was passed.

Faraday also made a smaller and simpler piece of apparatus by which electro-magnetic rotations could be shown. It consisted of a piece of glass tube, the lower end of which was closed by a cork through which passed a soft iron rod as shown in the diagram (Fig. 38). A little mercury was poured in, and the end of the rod made to project above the mercury. The upper end was also closed by a cork through which a piece of platinum wire passed ; a second wire was allowed just to touch the mercury, and was hung from a loop at the end of the first wire. In this way Faraday was able to obtain rotations when a current from a small voltaic cell was passed through.

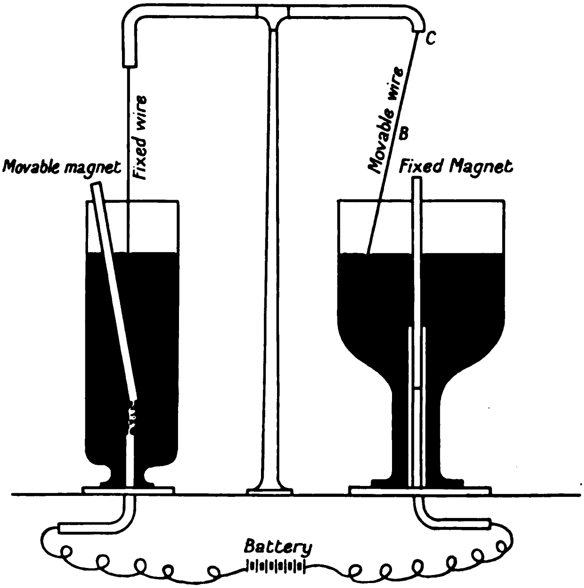


FIG. 37.

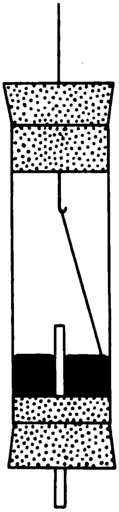


FIG. 38.

§ 4. *The Middle Period of Faraday's Career*

Before publishing an account of his results, Faraday tried to get into touch with Dr. Wollaston, as he wished to refer to his views with regard to electric rotations. He was not able to secure an interview, however, and unfortunately the paper was published without any reference to Wollaston's opinions. Immediately afterwards remarks were made affecting Faraday's honour. He was charged with not acknowledging information received while assisting Davy, and with taking Wollaston's thoughts and pursuing them as his own. Needless to say, such false and petty charges were extremely painful to Faraday, doubly so as he was young and at the beginning of his scientific career. Moreover, at this time his name was before the Royal Society as a candidate for fellowship. Faraday at once wrote to Wollaston, making a full apology for the unintentional wrong he had done, and at the same time explaining how he had come to perform the experiments. At first Faraday approached Wollaston through the mediation of a friend, but afterwards saw him personally. Wollaston, an older man with an established reputation, adopted a cold and supercilious manner in replying to Faraday's explanations, and Davy, who should have been his foremost defender, also behaved ungenerously. Ultimately the trouble blew over, although the miserable proceedings dragged on for nearly two years. There seems to be no doubt that Davy was jealous of Faraday, and did everything in his power to oppose his election to a fellowship of the Royal Society. Many years after, when he had received no less than ninety-five honorary titles and orders of merit, Faraday said: 'One title, namely that of F.R.S., was sought and paid for; all the others were spontaneous offerings of kindness and goodwill.' Faraday became a Fellow of the Royal Society in 1823. At this time he was engaged on some important researches on chlorine, and it was because he was 'eminently conversant in chemical science' that he was elected. We must confine ourselves, however, to a consideration of his work on electro-magnetism, which, beginning in 1821 with the experiments we have described, culminated ten years later with his great discovery of induced currents.

In 1825 Faraday was promoted to the position of Director of the Laboratories of the Royal Institution. One of the first things he did was to organize meetings on Friday evenings, to which members and their friends could gather together for lectures and discussions. These evenings soon became very popular, for Faraday was a fascinating lecturer and able to impart some of his own enthusiasm to his hearers. At this time he had a great deal on hand, for in addition to his ordinary duties at the Institution, he was busy with some important experiments on the use of different kinds of glass for optical purposes. But his diary and letters show that his great desire was to continue his researches on electro-magnetism. He firmly believed that since a magnet is deflected by an electric current, so a current ought to be affected in some way by a magnet. It was this idea that guided him through the years that followed and which led to his final achievement.

It would be well to consider, for a moment, how scientific discoveries come about. Popular stories such as those of Newton lying in his orchard and watching an apple fall, and of Watt experimenting with a tea-kettle, apart from their doubtful authenticity, are misleading because they seem to teach that scientific discoveries are easily made and often the result of chance. But in the case of every so-called accidental discovery, we find that the final synthesis could only have been by someone already familiar with the whole train of preceding facts. As Lagrange once said when speaking of scientific discoveries, 'accidents only happen to those who deserve them.' Francis Bacon held that on searching for truth, we must first make all possible observations, perform all possible experiments, tabulate all the results, then make a grand survey and see what phenomena correspond with other phenomena, and so find out the relations between different sets of facts and finally arrive at the generalisation or scientific law. But the history of science shows that, except, perhaps, in the purely descriptive sciences like natural history, discoveries are never made according to the pattern laid down by the Lord Chancellor. Usually at the very beginning of the enquiry, the imagination of the experimenter comes into play. He makes certain suppositions or hypotheses and thereby limits the number of possible experiments, and these hypotheses are not wild guesses without foundation, but are the results of an intensely active yet disciplined imagination.

The researches of Faraday afford an excellent example of true scientific method. Faraday began by making himself absolutely familiar with the whole field of knowledge of electrical and magnetic phenomena then existing. He never proceeded in a haphazard fashion, but always with some definite object in view. He succeeded where other men failed because, apart from his untiring energy and desire for truth, he had the insight of genius and saw possibilities where lesser men would have groped in confusion. Faraday did not stop when he had succeeded in making a magnet rotate round a current and a current round a magnet; he felt that there must be some relation between these rotations and those noticed by Arago. He felt that the action of a current on a magnet noticed by Oersted, and that of current on current noticed by Ampère, must be due to some common cause. The discovery of this cause might give the clue to the reason for electro-magnetic rotations and other phenomena. It must be remembered that although Ampère had come forward with a mathematical theory of electro-magnetism, the ideas held by scientific men at the time were very hazy. Oersted, as we have seen, had spoken of the 'conflict of electricity.' Others had dealt with the forces acting circumferentially round a wire carrying current. But in every case the force was looked for in the actual conductor or in the magnet, as the case might be.

Faraday introduced a new conception with the subject. He conceived the forces to be due to tensions and strains in the *medium* surrounding the magnet or conductor. He was no mathematician, and problems were not solved for him when they were expressed in mathematical language, so that he seems to have needed some means of visualising the actual physical conditions taking place. It was for this reason that he put forward his conception of lines of force, but before we can appreciate the importance of this conception, we must go back and consider his experiments in detail.

§ 5. *Electro-magnetic Induction*

Fortunately for us, Faraday has given a full account of his investigations.[1] The descriptions are of particular interest, as they were written at the time of the experiments. We are thus able to realize in some measure how he worked and how he arrived at his conclusions. In the first series of his researches he tells us that he set out to see if magnetism could give rise to electricity and if one current could induce another current in a neighbouring conductor, just as electricity produced by friction can induce an electric charge on another body. He extends the term ' induction,' which was in general use in connection with the phenomena of frictional electricity, to the possible effect of current electricity on a neighbouring body. He tells us that certain effects of induction had already been observed, for instance those of Arago on rotations. But he says that it is unlikely that these are all the effects that can be produced. He then proceeds to describe his first attempts to produce electricity from magnetism.

He took a helix or coil of wire and connected the ends to a galvanometer. The instrument used was a multiplier (see p. 74), consisting of a coil of several turns of wire, fixed with its plane in the magnetic meridian, and having a compass needle supported horizontally at its centre. Faraday placed a magnet inside the helix, but tells us that he could not detect any effect on the galvanometer. The negative result must have been due either to a lack of sensitiveness of the galvanometer, or to the momentary character of the effect. In November of the same year he attempted to induce a current in a conductor placed in the main circuit. Again the momentary effect must have escaped him, for he tells us that he found 'no result.' In December 1825[1] and in April 1828 he made similar experiments, but still obtained no positive results.

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[1] *Experimental Researches in Electricity*, 3 vols., London, 1839.

Meanwhile, Faraday was occupied with lectures and business affairs, and his reputation was rapidly increasing. In 1826 he was relieved from his duties as chemical assistant at the Royal Institution that he might have more time for research. In 1827 he was offered the Professorship of Chemistry in the University of London, then newly founded. This he declined as he could not bring himself to leave his dearly-loved Royal Institution. He had many honours conferred on him from scientific societies in other countries, and letters he received from members of the French Academy, notably Hachette and Ampère, show that his opinions were held in high esteem.

In 1831 he returned to his experiments on the induction of currents, and this time he met with success.[2] He began to work in August of that year and continued at intervals until November, the actual experiments occupying only ten days. After long seeking and repeated disappointments, his great work of creation was thus completed in this short time. They are days memorable in the history of science. We will describe his first experiment in his own words :

> 'I have had an iron ring made . . . $\frac{7}{8}$ of an inch thick and six inches in external diameter. Wound many coils of copper round, one half of the coils being separated by twine and calico : there were three lengths of wire, each about twenty-four feet long, and they could be connected as one length or used as separate lengths. By trial with a trough each was insulated from the other. Will call this side of the ring *A*. On the other side, but separated by an interval, was wound wire in two pieces, together amounting to about sixty feet in length, the direction being as with the former coils. This side call *B* (Fig. 39). Charged a battery of ten pairs of plates four inches square. Made the coil on *B* side one coil, and connected its extremities by a copper wire passing to a distance, and just over a magnetic needle (three feet from the iron ring), then connected the ends of one of the pieces on *A* side

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[1] *Quarterly Journal of Science,* July 1825.

[2] *Exp. Researches,* §§ 1-60.

> with battery: immediately a sensible effect on needle. It oscillated and settled at last in original position. On breaking connection of *A* side with battery again a disturbance of the needle.'

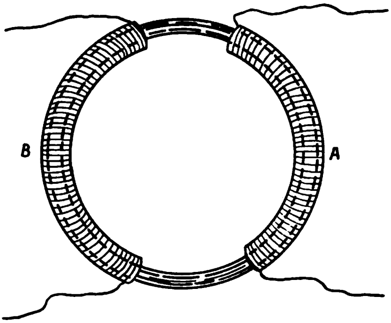

FIG. 39.—FARADAY'S RING.

On the 30th of August he wrote in his note-book: 'May not these transient effects be connected with causes of difference between power of metals at rest and in motion in Arago's experiments?' On 23rd September he wrote to a friend: 'I am busy just now again on electro-magnetism, and I think I have got hold of a good thing, but can't say. It may be a weed instead of a fish that, after all my labour, I may at last pull up.' The next day, 24th September, which was the third day of his experiments, he again tried to detect an inducing action of one current on a conductor placed near. The entry for that day was: 'No induction sensible.' Later on the same day, however, he modified his first experiments, using bar magnets instead of an iron ring (Fig. 40). He says:

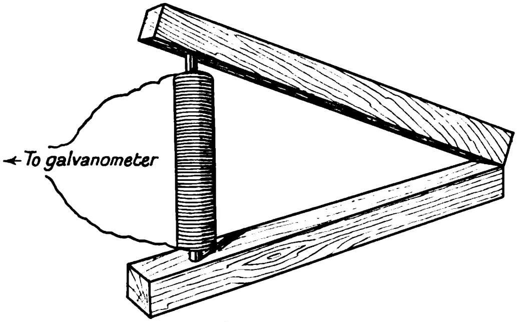

FIG. 40.

> 'An iron cylinder had a helix wound on it. The ends of the helix were connected with the indicating helix at a distance by a

> copper wire. Then the iron placed between the poles of bar magnets as in the figure. Every time the magnetic contact at *N* or *S* was made or broken, there was magnetic motion at the indicating helix—the effect being, as in former cases, not permanent, but a mere momentary push or pull. But if the electric communication (*i.e.* by the copper wire) was broken, then the disjunction and contacts produced no effect whatever. Hence here distinct conversion of magnetism into electricity.'

The fourth day of his experiments was 1st October, and on this day he made his great discovery of induced currents.

> 'One of the coils (of a helix of copper wire 203 feet long) was connected with the flat helix, and the other coil of same length round same block of wood with the poles of the battery (it having been found that there was no metallic contact between them), the magnetic needle at the indicating flat helix was affected by so little as to be hardly sensible.
>
> In place of the indicating helix, our galvanometer was used, and then a sudden jerk was perceived when the battery communication was *made* and *broken*, but it was so slight as to be scarcely visible. It was one way when made, the other when broken, and the needle took up its natural position at intermediate times. Hence there is an inducing effect without the presence of iron.'

The fifth day was 17th October, when he discovered that an electric current could be produced by the movement of a magnet near a wire (Fig. 41). He describes the experiments as follows:

> 'A cylindrical bar magnet three-quarters of an inch in diameter, and eight inches and a half in length, had one end just inserted into the end of the helix cylinder (220 feet long), then it was quickly thrust in the whole length, and the galvanometer needle moved; then pulled out, and again the needle moved, but in the opposite direction. This effect was repeated every time the magnet was put in or out.'

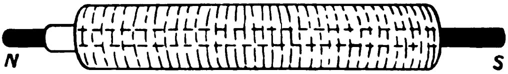

Fig. 41.

On the ninth day of his work, 28th October, he reversed the procedure. Instead of moving a magnet through a coil of wire, he arranged that a conductor in the form of a copper disc should be made to turn between the poles of a magnet. For this purpose he used the great horse-shoe magnet that is still to be seen at the house of the Royal Society. The axis and edge of the disc were connected to a galvanometer, and as the disc turned, the needle of the galvanometer was deflected, showing that an induced current had been produced.

The next day that he returned to his investigations was 4th November. This time he took a copper wire, connected it to a galvanometer placed some feet away, and moved it quickly between the poles. As he moved the wire, he noticed that the needle of the galvanometer was deflected, showing that again an induced current had been produced. Let us now summarize his results: Faraday showed that induced currents are produced in a closed circuit under the following conditions:

1. When a magnet is brought near the circuit.
2. When the circuit itself is moved about in the presence of another current or magnet.
3. When the current in a neighbouring circuit is made or broken.

A current gives rise, as we have seen, to a magnetic field, and the above results are therefore included in the single statement that induced currents are produced whenever there is a relative change in the magnetic conditions.

Faraday had noticed that in each case the induced current at the end of the experiment was opposite in direction to that at the beginning. Later, a Russian physicist, Emil Lenz, pointed out that the direction of the induced current is always such as to oppose the original motion which produced it.[1] Some two or three years after his first series of discoveries on induced currents, Faraday succeeded in obtaining an induced current by rotating a coil in the earth's magnetic field: this effect he called 'Terrestrial magneto-electric induction.' He also showed that any variation in the strength of a current induces a current in the circuit itself. This induced current opposes, as it were, the actual change in strength, lessening the rate of increase of the current strength, and making the rate of decrease slower. This phenomenon Faraday called *the inductive action of a current on itself*; it is now called *self-induction.*

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[1] *Ann. d. Phys.* xxxi. (1834), p. 483.

§ 6. *Faraday's Conception of Lines of Force*

In describing the last two experiments, Faraday speaks of the conductor as 'cutting the magnetic curves,' and in a note to the paper he says: 'by magnetic curves, I mean lines of magnetic forces which would be depicted by iron filings.'[1] Now it had long been known that if iron filings are sprinkled on a sheet of paper and a magnet held underneath, the filings set themselves in definite curves. Faraday had, of course, noticed this effect. The curves suggested to him the idea of *lines of magnetic force*, the direction of a line at any point giving the direction of the magnetic force. Faraday conceived all space to be filled with such lines, each line forming a complete curve, returning ultimately to the point from which it began.[2] Faraday also represented the strength of the magnetic field at different places by the spacing out of the lines of force.

> 'The relative amount of force, or of lines of force in a given space, is indicated by their concentration or separation—*i.e.* by their number in that space.'[3]

Thus the field is strong where the lines are closely packed together and weak where they are spread apart. In his later writings, as well as in his papers on the induction of currents, Faraday constantly made use of his conception of lines of force. Thus, writing in 1851, he said:

> 'I cannot refrain from again expressing my conviction of the truthfulness of the representation, which the idea of lines of force affords in regard to magnetic action. All the points which are experimentally established in regard to that action . . . appear to be well and truly represented by it.'[4]

We have seen that Faraday's experiments showed that for the production of induced currents there must be a relative change

[1] *Exp. Researches*, § 114.

[2] *Ibid.*, vol. iii. p. 405.

[3] *Ibid.*, § 3122.

[4] *Ibid.*, § 3174.

in the magnetic conditions. The bar magnet or coil carrying current supplied a magnetic field, then the conductor was moved so that it cut through the lines of force of the field; or, on the other hand, the magnet itself was moved through the coils of the conductor: when a conductor carrying current is in a magnetic field, Faraday supposed the medium to be in a peculiar condition which he called the *electro-tonic state.*[1] Further, Faraday showed that the magnitude of the induced current depended on the conducting power of the wires, thus pointing to the conclusion that a definite electromotive force is set up. He then showed that there is a simple relationship between the induced electromotive force and the rate of cutting through the lines of force. He said:

> 'Whether the wire moves directly or obliquely across the lines of force, in one direction or another, it sums up the amount of the forces represented by the lines it has crossed . . . the quantity of electricity thrown into a current is directly as the number of curves intersected.'[2]

Using the notation of the calculus, we should say:

$$e = -\frac{dN}{dt},$$

where e is the induced electromotive force and $\frac{dN}{dt}$ is the rate at which the lines of force are cut through. On this generalisation we can interpret all cases in which induced currents are produced.

It is of interest to consider the other phenomena of electromagnetism we have described, in the light of Faraday's conception of lines of force. He supposed the lines of force to possess certain physical properties—a tendency to shorten and a mutual repulsion. This was equivalent to supposing that in the magnetic field there are stresses acting, consisting of a tension along the lines of force and a pressure at right angles to them.

Let us first consider Ampère's results. Ampère showed that two parallel wires forming a circuit attract one another if the currents flowing in them are in the same direction, and repel one another if the currents are in opposite directions. Now it can be shown by means of a small compass needle that the lines of force in the neighbourhood of a straight wire carrying current are concentric circles (Fig. 42). Assuming therefore the state of tension and mutual repulsion of the lines of force, it is evident that the resultant field due to currents in the same direction in two neighbouring wires will be such that they will be driven from the strong parts of the field to the weaker parts, and so urged together (Fig. 43). If the currents are in opposite directions, the conductors are driven apart (Fig. 44).

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[1] *Exp. Res.*, § 1729.

[2] *Exp. Res.*, §§ 3082, 3155.

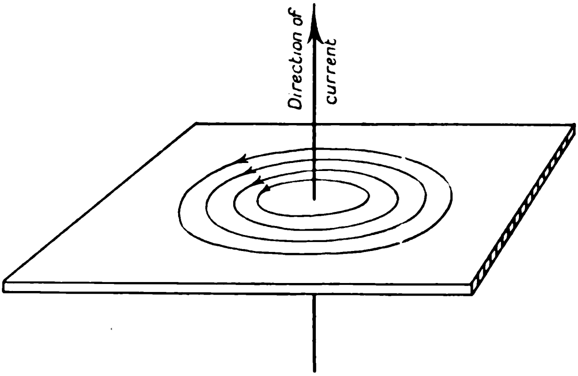

FIG. 42.—LINES OF FORCE
due to a current in a straight conductor

Again, it will be remembered that Faraday had succeeded in making a magnet rotate round a wire carrying a current, and conversely he had caused a wire carrying a current to rotate round a magnet. In each case the movement can be explained if we admit that the distribution of the lines of force due to both current and magnet sets up certain stresses in the medium. It is then easy to realize how the wire or magnet, as the case may be, is continually urged away from the strong part of the field and so made to rotate.

Until the work of Faraday, no explanation was forthcoming of the curious case of rotation noticed by Arago, to which we have already referred (p. 58). Arago had been surprised to find that if a copper disc be rotated beneath a suspended magnet, the magnet itself would follow the movements of the disc. Now in the light of Faraday's discoveries, and with the help of his conception of lines of force, we can understand the behaviour of the magnet. As the disc moves, it cuts through the lines of force of the magnet, and induced currents are therefore set up. The movement of the magnet is then simply the result of the mutual action of the magnetic fields due to the induced current and to the magnet. Thus by endowing the lines of force with certain

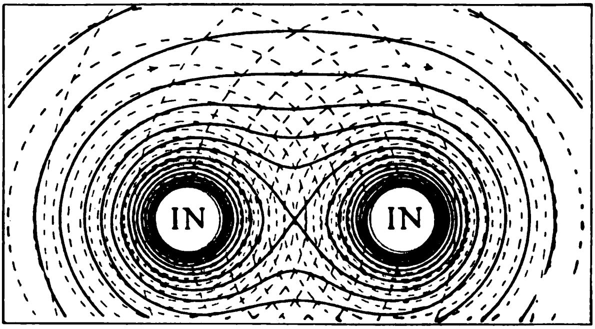

FIG. 43.—RESULTANT FIELD
due to two currents in the same direction

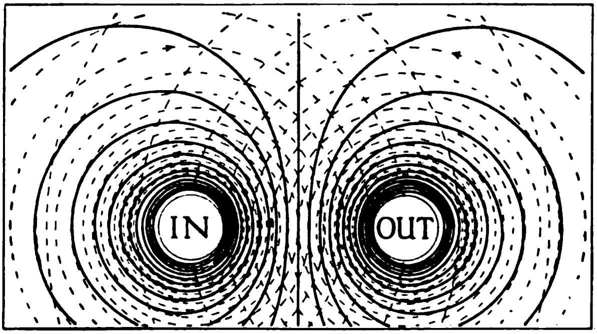

FIG. 44.—RESULTANT FIELD
due to two currents in opposite directions

physical properties, we can visualize what takes place, and we can link together a number of otherwise disconnected phenomena. Indeed, it is impossible to over-estimate the importance of Faraday's conception in the study of the science of electricity.

§ 7. *Later Work of Faraday*

Faraday's discovery of electro-magnetic induction marks the highest point of his achievements,[1] but his further researches resulted in a great number of other important discoveries. To some of these we will briefly refer.

We have seen how the discoveries of Oersted and Ampère followed by those of Faraday showed the close connection between magnetism and electricity. But there was a gap between the different branches of electrical science. Thus electricity produced by friction seemed to be a surface phenomenon, whereas electricity derived from a voltaic cell seemed to be conducted through the interior of substances. In 1833 Faraday succeeded in showing that every known effect of electricity—heat, light, chemical change, magnetic phenomena, physiological reactions—could be produced, whether the electricity was obtained by friction or from a cell. In this way he showed the essential identity of the two forms. Faraday also carried out important quantitative investigations in electrostatics.

His experiments with voltaic cells led on to a series of researches on the electrolytic decomposition of solutions which resulted in the establishment of the two Laws of Electrolysis so well known to all students of chemistry and physics. (See Chapter VIII.) Faraday also investigated the magnetic properties of substances other than iron. He found that cobalt and nickel were magnetic in the same way as iron, though to a much less extent. By suspending a number of different substances in turn between the poles of a powerful magnet he found that some of them, notably bismuth and heavy glass, set themselves at right angles to the lines of force, whereas a piece of iron always lies along the lines. This opposite behaviour of certain substances he called *Diamagnetism*.

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[1] The phenomenon of self-induction was observed independently shortly after Faraday's discovery by Joseph Henry, of New Jersey, U.S.A. In publishing the results, however, he acknowledged the priority of Faraday's work.

Faraday often sought to find connecting links between various phenomena, and in 1845 succeeded in discovering a relation between light and magnetism. His experiments consisted in subjecting what is known as *plane-polarized* light to the action of a powerful magnetic field. Ordinary light consists of waves in every possible plane, but under certain circumstances, notably when light passes through a crystal such as tourmaline or Iceland spar, the vibrations constituting the waves are confined to one plane. The light is then said to be plane-polarized. Faraday showed that a magnetic field causes the plane of polarization to rotate. We cannot here attempt to describe the details of his experiments, but it is interesting to notice the titles of his papers at this time: *Thoughts on Ray Vibrations . . . On the Magnetization of Light, and the Illumination of Magnetic Lines of Force.* May it not be that Faraday, with his boldness of imagination, had already come near to conceiving an electro-magnetic theory of light?

Now a word about Faraday, the man. His private life was very simple, and he lived and died a poor man. Shortly after his discovery of electro-magnetic induction, Faraday, whose salary at that time was £100 a year together with house, coal and candles, was elected to a professorship which had just been founded by a certain Mr. Fuller. The appointment carried a salary of about £100 a year, and Faraday remained 'Fullerian Professor' for thirty-four years. Yet he could have been rich had he chosen to give his time to investigations for which the commercial world was clamouring. His choice of pure research left him poor, but as Tyndall said: 'his was the glory of holding aloft among the nations the scientific name of England.'

Faraday was a strenuous worker, and sometimes remained at his investigations for so long that his health suffered. More than once he had a serious breakdown which necessitated a long period of rest, but fortunately change of scene and the devoted care of his wife restored him. He had no children of his own, but used to delight in the presence of young people. Always a delightful lecturer, he was at his best when talking to children, and his Christmas lectures at the Royal Institution show how great was his skill in exposition.

By universal consent Faraday is regarded as the greatest of experimental philosophers. Perhaps his leading characteristic was reliance on facts derived from experiments. 'Without experiment, I am nothing.' . . . 'All our theories are fixed upon uncertain data, and all of them want alteration or support from facts,' he wrote. Another characteristic was his marvellous insight by which he foresaw results, and afterwards by his experiments showed them to be true.

His declining years were spent in retirement at Hampton Court, where apartments were placed at his disposal by Queen Victoria. After a long illness, he passed away in 1867. Faraday was respected by all who knew him for his kindness and for the uprightness of his character. He received at one time or another almost every honour that the learned societies of the world could give. Yet he remained to the last the humblest of men, and his humility as well as his love of truth were but the expressions of that deep sense of religion which was the guiding principle of his noble life.

VI

ELECTRICAL MEASUREMENTS AND SOME PRACTICAL APPLICATIONS

§ 1. *Applications of Faraday's Discoveries*

THE discovery of electro-magnetic induction was the starting-point for the utilization of electricity on a large scale, and for the application of such power for lighting and traction. Faraday's copper disc rotating between the poles of a magnet, described by him in 1831 (see p. 95), constituted the first magneto-electric machine or *dynamo*.

A modern dynamo is of complicated design, but it consists essentially of a suitable conductor, built up of many coils, which is made to rotate in a magnetic field (Fig. 45). The rotating conductor or *armature*, as it is called, cuts through the lines of force of the magnetic field, and an induced current is thereby set up in the coils of the armature. In each coil the induced current changes its direction during each revolution. Such a current is said to be an *alternating* one. By means of a device called a *commutator* the *alternating* current may be made *direct* by reversing the direction of the current in each coil of the armature every time it passes a pair of conductors or *brushes*.

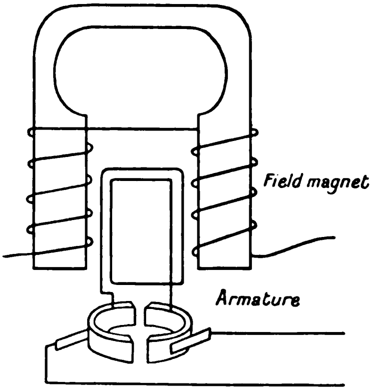

FIG. 45.—SIMPLEST FORM OF DYNAMO OR MOTOR

The electric *motor* is the complement of the dynamo. In the motor a current is led into a conductor which is free to rotate between the poles of a powerful magnet. The mutual action between the magnetic fields due to the current and the magnet causes the conductor to rotate continuously. The apparatus devised in 1821 by Faraday (see p. 87) foreshadowed the motor of the present day. Curiously enough, the motor was brought to a fair state of development at an early date, while the dynamo long remained but a scientific toy. In 1839 a boat was propelled along the River Neva at a rate of 2¼ miles per hour by means of an electric motor. No wonder that in those days there were no regulations concerning speed limits! In the early forms of motor, the current was obtained from batteries of voltaic cells, sometimes as many as seventy being used.

The construction of powerful motors required high electromotive forces to excite the electromagnets. This was not possible until some better source of current than the ordinary chemical cell had been devised. There was also the question of expense. During a discussion at the Institution of Civil Engineers in 1857, the cost of running an electric motor by means of Daniell cells was computed. The cost of the zinc used in the cells was such that electrical power at that time was sixty times dearer than steam power. Consequently all the eminent engineers present voted against the use of electrical power. After 1870, however, great improvements were made in the construction of dynamos, and the production of electricity on a large scale thus became cheapened. Electric light, electrical power for manufacturing purposes, for domestic heating, and for tramcars and trains thus came within the range of commercial development.

Faraday's iron ring wound with two coils of wire was the prototype of the modern *induction coil.* Such a coil enables us to obtain a very high electromotive force from the current given by a very few voltaic cells. After the time of Faraday many experimenters attempted to construct apparatus which should give a high electromotive force by the inductive action of one circuit on another. The first effective apparatus was devised in 1851 by Ruhmkorff (1803-1877), an instrument-maker living in

Paris. The induction coil as improved by Ruhmkorff consists essentially of two coils wound on an iron core made up of a bundle of iron wires (Fig. 46). The inner coil, or *primary*, consists of a few turns of thick wire; the outer coil, or *secondary*, consists of thousands of turns of very fine and carefully insulated wire. The current in the primary is continually made and broken by means of a simple device similar to that in the familiar electric bell. By the repeated interrupted currents in the primary a series of electromotive forces are produced in the secondary coil. The induced electromotive force is very large, because the lines of force due to the primary pass through many turns of the secondary. By the use of the condenser, the induced electromotive force at the 'break' of the primary current is rendered greater than that at 'make.'

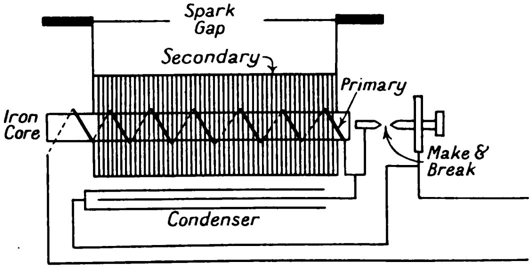

FIG. 46.—INDUCTION COIL

The practical application of induction coils is very wide and various. They are largely used in physical research, and, being necessary for the production of X-rays, they are to be found in all modern hospitals. Induction coils have an extensive use in wireless telegraphy. The *magneto* which gives the spark required to explode the mixture of gases in an internal combustion engine is a modified form of induction coil. It is, in fact, a revolving induction coil, and the current in the primary, instead of being derived from cells, is produced by the revolution of the two coils, primary and secondary, between the poles of a fixed magnet (Fig. 47).

An induction coil is used for the production of a high electromotive force by repeatedly interrupting the direct current in the primary. But if an alternating current passes through the primary coil, no such interruption of the current is necessary since the alternations of the current produce the necessary changes in the lines of force threading through the secondary circuit. Consequently an alternating current may be changed from a high to a low electromotive force or vice versa by a simple piece of apparatus known as a *transformer* (Fig. 48). This consists essentially of two coils, a primary and a secondary, wound on the same iron core. The number of turns in these coils determines whether the electromotive force is lowered or raised. Transformers are largely used in the transmission of electrical power.

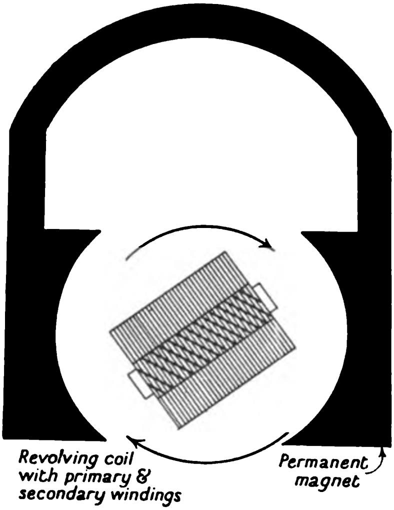

FIG. 47.—THE MAGNETO

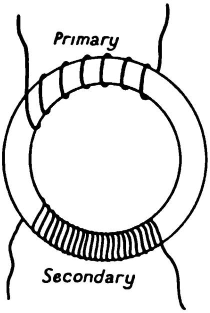

FIG. 48.—THE TRANSFORMER

The telephone is another example of the

practical application of induced currents. In its simplest form it consists of a horse-shoe magnet with coils of insulated wire round its poles (Fig. 49). Just within the mouthpiece is a very thin flexible iron sheet or diaphragm, so arranged that it is a short distance away from the poles of the magnet. When one speaks into the mouthpiece the voice sets up vibrations in the air which are conveyed to the diaphragm. Iron being magnetic, the movements of the diaphragm change the number of lines of force through the coils of the wire, and thus a current is induced. This current passes from the coils to wires which eventually reach the receiving instrument. The listener at the other end holds to his ear a similar instrument. The transient currents circulating in the wires pass to the coils, and there change the strength of the field due to the magnet. Hence the force of attraction of this magnet on the iron diaphragm changes. Thus the diaphragm is made to move to and fro. These movements, which are extremely rapid, set up vibrations in the air which are heard as sounds by the listener. The 'loud-speakers' used in connection with wireless reception depend on an elaboration of the same principle.

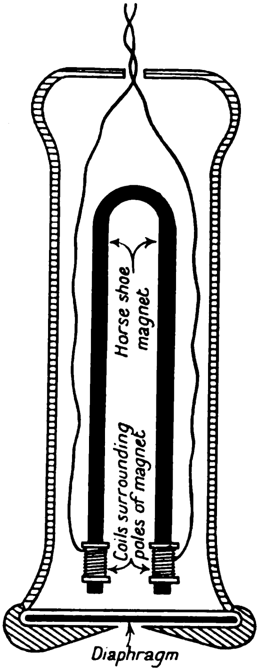

FIG. 49.—SIMPLEST FORM OF TELEPHONE TRANSMITTER

§ 2. *Early Attempts to measure Electrical Resistance*

The mid-nineteenth century was a period of consolidation of electrical theory rather than one of striking advance in the knowledge of electrical phenomena. Great progress was made, however, in exactness of measurement, and the mathematical physicists of the time linked together diverse phenomena into coherent theories. A modern physical laboratory, with its delicate instruments for the estimation of electrical quantities, is among the concrete results achieved by the experimenters of the middle and late nineteenth century.

When the importance of Ohm's work was recognized, investigators turned their attention to the accurate measurement of resistance, current and electromotive force, though the designing of instruments and the adoption of suitable units took many years to accomplish. A number of important laboratory devices were designed by Sir Charles Wheatstone (1802-1875), for many years Professor of Physics at King's College. Wheatstone is best known for his many contributions to the practical side of telegraphy, but his skill and resource were also used in the field of pure physics. He was one of the first in this country to appreciate the significance of Ohm's Law. In 1843 he began a series of experiments based on this law.[1] He chose as his unit of resistance that of a uniform copper wire 1 ft. long, weighing 100 grains. He improved on Nobili's astatic galvanometer (see p. 75) by having a larger scale and using a microscope to measure the deflections. Wheatstone's first method for the measurement of resistance was of the simplest character. It consisted in using a constant battery and observing the galvanometer deflection first with the unknown resistance in the circuit, and afterwards with an added known resistance. Calling the electromotive force of the battery E, and the current strength in the two cases F and F^1, R the unknown and r the known resistance, it follows from Ohm's Law that:

$$F = \frac{E}{R},$$

$$F^1 = \frac{E}{R+r};$$

$$\therefore \frac{F}{F^1} = \frac{R+r}{R};$$

---

[1] *Phil. Trans.* 1843, p. 303.

and since the ratio of the galvanometer deflections gives us the ratio $\frac{F}{F^1}$, the value of R can be calculated. In later experiments, Wheatstone avoided any actual measurement of the deflection by keeping the current constant. To attain this end he devised a means for varying his known resistance by any desired amount. This instrument, which Wheatstone called a *rheostat,* is familiar to all students of physics.

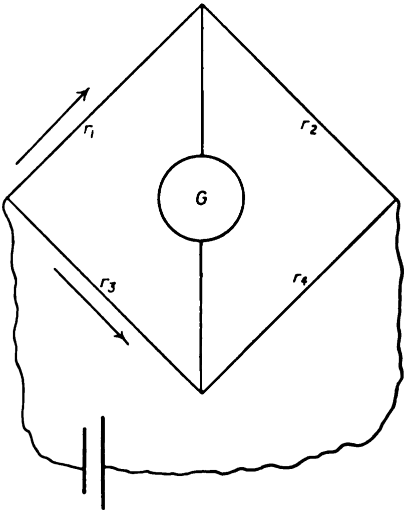

FIG. 50.—CHRISTIE'S RESISTANCE BALANCE

An important fact in connection with a circuit of four conductors had been noticed by the mathematician S. H. Christie (1784-1865). He found that when a current divides itself among four resistances joined in quadrilateral form, the battery being connected to one pair of opposite corners and a galvanometer to the other pair, it is possible to adjust the resistances so that the galvanometer is not deflected (Fig. 50). When such a condition is realized, it follows from Ohm's Law that there is a simple proportionality between the four resistances r_1, r_2, r_3, r_4, which may be written $\frac{r_1}{r_2} = \frac{r_3}{r_4}$. It is evident that one known resistance is sufficient, provided we know the ratio of the other pair. Wheatstone constructed several resistance balances in which a piece of uniform wire, tapped by means of a sliding contact, constituted one pair of conductors, the required ratio being obtained from the ratio of the lengths. Such a network of conductors has since been known as *Wheatstone's Bridge* (Fig. 51).

The great advantage of the Wheatstone's Bridge method for finding resistance lies in the fact that a *null method* is employed.

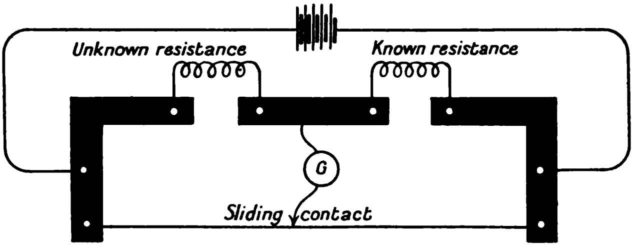

FIG. 51.—WHEATSTONE'S BRIDGE
with uniform wire and sliding contact

One effect is balanced against another, and no actual measurement of the galvanometer deflection is required. It will be remembered that Ampère had pointed out the advantage of null methods in physical experiments, and had used them in his own researches.

§ 3. *Improvements in Electrical Apparatus*

A disadvantage of the ordinary galvanometer with circular or rectangular coils (see p. 74) lies in the fact that the needle does not swing in a uniform magnetic field. To remedy this defect, Hermann von Helmholtz (1821-1894) devised in 1849 a different type of galvanometer. In his instruments two equal coils were fixed at a distance apart equal to their radii. This ensured a more uniform field at the centre. In both the tangent and Helmholtz form of galvanometer the deflection had to be measured by a pointer attached to the pivoted magnet. It became customary to use a long pointer and a large scale. But this was not without its disadvantage, because lengthening the pointer also increased its weight.

A great improvement in the measurement of small deflections was made the same year by Wilhelm Weber (1804-1890). He devised the mirror and scale method in which a beam of light is reflected from a small mirror attached to the moving magnet. The reflected beam may be compared to a very long, weightless pointer. The advantage of this method was soon recognized, and it was adopted in many different types of instruments. Weber also invented the *Electrodynamometer*, an instrument for the measurement of the attractions and repulsions due to electric currents. This was probably the first delicate instrument made for the measurement of current.[1]

Weber and Gauss (1777-1855) carried out extensive researches on terrestrial magnetism.[2] For this purpose a magnetic observatory was built at Göttingen. This became the centre for the *Magnetic Union* founded by Gauss and Weber for the simultaneous recording of magnetic observations. The most important of the instruments designed by Weber and Gauss was the *Magnetometer*. This consisted of a magnet suspended by two wires, the deflection of the magnet being measured by the mirror and scale method. The instrument was used in the determination of the horizontal component of the earth's magnetic force. A knowledge of the value of this force at any particular place is of great importance in many electrical determinations (see below, p. 115).

§ 4. *William Thomson—Lord Kelvin*

A new impetus was given to the measurement of electrical quantities by the work of William Thomson, afterwards Lord Kelvin (1824-1907).[3] Thomson, who was born at Belfast, went to live at Glasgow when his father was appointed to the chair of Mathematics there. He matriculated at the age of ten, and entered the University of Glasgow. Studying mathematics later at Cambridge, he became Second Wrangler and first Smith's Prizeman. At that time there were no facilities for the study of experimental science at Cambridge, or indeed for that matter, at any other British University. Thomson therefore proceeded to continental seats of learning to obtain experience in manipulative methods. On his return at the age of twenty-two he was appointed to the chair of Natural Philosophy at Glasgow. His work there was a source of inspiration for men of science for more than fifty years, and marks a period in our subject. Perhaps the chief characteristic of Thomson's genius was his emphasis on the importance of measurement.

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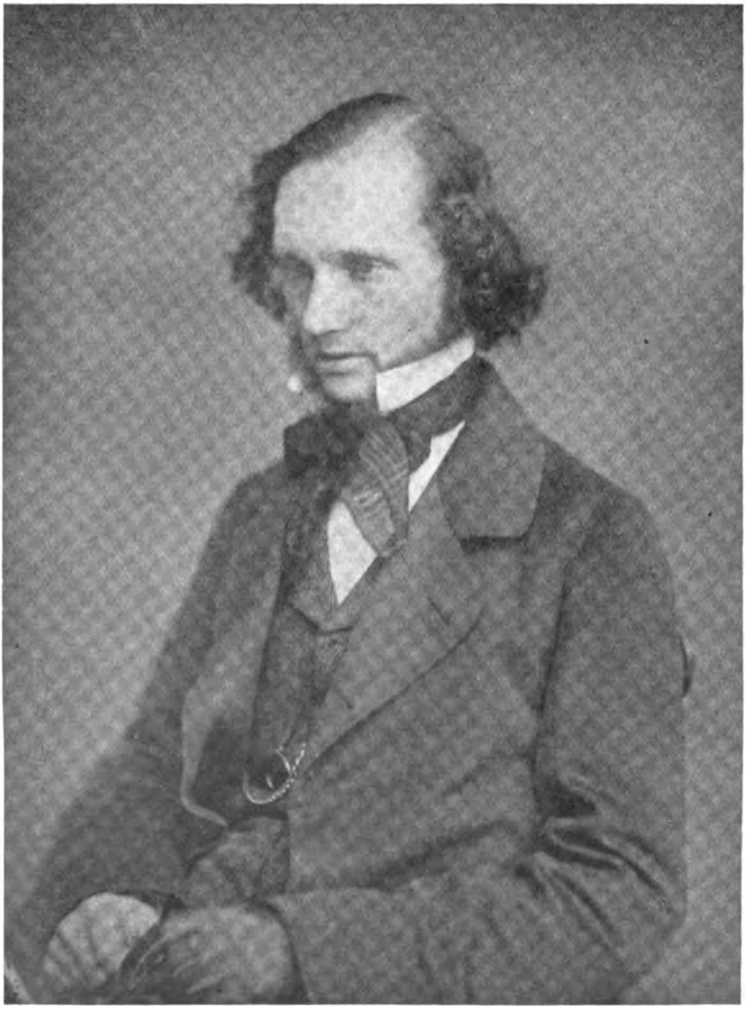
[1] Poggendorff's *Annalen*, lxxiii, 1848, p. 193. Translated in Richard Taylor's *Scientific Memoirs*, London, 1852, vol. v. p. 489.

[2] Poggendorff's *Annalen*, vol. xix. p. 361.

[3] *Life of Lord Kelvin*, S. P. Thompson, 2 vols., London, 1910.

> 'When you can measure what you are speaking about and express it in numbers, you know something about it, and when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind.'

A few years after his appointment to the Glasgow chair, Thomson's attention was called to some of the problems connected with telegraphy. He investigated mathematically the speed of transmission through cables, and pointed out the necessity for the use of pure copper of high electrical conductivity. He then set to work to devise better instruments for detecting and recording telegraphic signals. The most important of such instruments were the *Siphon Recorder* and a sensitive form of *Mirror Galvanometer* with a very small needle and mirror. Thomson showed that the astatic galvanometer (see p. 75), although delicate, has one grave disadvantage. Since the controlling magnetic field is reduced to a minimum, the needle is easily affected by stray magnetic fields. He therefore reversed matters so that instead of having a magnetized needle suspended within a coil, he suspended a coil between the poles of a strong permanent magnet. Such a galvanometer is independent of the earth's field or of any other weak magnetic field. Most sensitive galvanometers at the present time are of this *moving coil* type.



LORD KELVIN

Thomson's investigations in telegraphy led to the invention of many other instruments, and his researches involved the measurement of every kind of electrical quantity. These measurements were of the *absolute* character (see p. 118), thus presenting a great advantage over the purely comparative methods that had preceded him. Now every measurement requires a unit, whether it be yards of ribbon, pounds of tea or electrical quantities that we are considering. Until Thomson's time only arbitrary electrical units were used by individual experimenters. These units were selected in accordance with their own requirements. Wheatstone, for instance, sometimes used certain lengths of telegraph wire as units of resistance. Such units, however, could only serve for the particular investigation on hand. When more workers entered the field it was realized that standard units were required for electrical measurements in order that different results could be compared, just as standard units of length and mass are necessary for the ordinary affairs of life. Those electrical units now employed were not finally decided until the closing years of the nineteenth century. From the time of Weber and of Thomson, however, it was perceived that such units must depend ultimately on the fundamental units of mass, length and time.

§ 5. *Units—Fundamental and Derived*

The three fundamental units are those of length, mass, and time. The unit of length is the *centimetre*, being one-hundredth part of a metre. The metre itself is theoretically the ten-millionth part of a meridian of the earth measured from the pole to the equator, but practically the length of a standard bar preserved in Paris. The unit of mass is the *gramme*. It is theoretically the mass of a cubic centimetre of distilled water at standard temperature and pressure, but practically the thousandth of a standard lump of platinum kept in Paris. The standard unit of time throughout the civilized world depends upon the time of rotation of the earth about its axis. For all scientific purposes the unit of time is one *second* of mean solar-time. The centimetre, gramme and second are thus the fundamental units for scientific measurements. From them we can define what are called the derived units, such as those of velocity, acceleration, force and work. Such derived units are said to belong to the centimetre, gramme, second or *C.G.S. system.*

Now the usual means for detecting electrical and magnetic disturbances are by the mechanical effects produced. The *electrostatic* unit of quantity is defined as that quantity which placed in air a unit of distance from an equal quantity of the same sign repels it with unit force. In the C.G.S. system the unit of force is the dyne, and is that force which produces in a mass of 1 gramme an acceleration of 1 centimetre per second per second.

When we come to the effect produced by a current flowing in a conductor we have a new unit to define. This unit, the *electromagnetic* unit, is based on the definition of the unit of strength of a magnetic pole. The unit magnetic pole is such that when placed in air 1 centimetre from a similar pole, it repels it with a force of 1 dyne. The electro-magnetic unit of current is defined as that current which flowing in a coil of wire of radius 1 centimetre produces at the centre a force of 2π dynes per unit pole.

§ 6. *Measurement of Electrical Quantities in Absolute Units*

(*a*) *The Horizontal Component of the Intensity of the Earth's Magnetic Field*

The method used by Gauss[1] is the one usually adopted at the present time. It consists in finding (i) the period of vibration of a magnet when suspended horizontally in the earth's field, and (ii) the angle through which the needle of a magnetometer in the earth's field is deflected by the same magnet placed a measured distance away.

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[1] Richard Taylor, *Scientific Memoirs*, London, 1841, vol. ii. p. 20.

For a full treatment of the subject of absolute measurements, see Andrew Gray, *Absolute Measurements in Electricity and Magnetism*, London, 1921.

The first determinations give the product MH, where M is the magnetic moment (see p. 122) and H the horizontal component required. The second determination gives the ratio $\frac{M}{H}$ in terms of the distance between magnetometer and magnet and the tangent of the angle of deflection of the magnetometer needle. From the values $\frac{M}{H}$ and MH, H can be determined in absolute measure.

(*b*) *Current*

The determination of current in terms of the electro-magnetic unit can be made with the aid of a *tangent galvanometer*. Such an instrument consists of a circular coil of one or more turns and a magnetized needle supported horizontally at the centre. The plane of the coil is placed in the magnetic meridian. The current is proportional to the *tangent* of the angle of deflection, hence the name of this particular type of galvanometer. We have seen (p. 71) that the intensity of the force at the centre of a coil of radius r through which a current of strength i is flowing, is given by the formula

$$\frac{i \cdot 2\pi}{r}.$$

If there are n turns in the coil, it follows from the principles established by Ampère that the intensity $= \frac{i \cdot 2\pi n}{r}$. If the needle at the centre of the coil is deflected through an angle θ, it is easily shown that the deflecting force $= H \cdot \tan\theta$.

Equating these forces, we have

$$\frac{i \cdot 2\pi n}{r} = H \tan\theta,$$

i.e.

$$i = \frac{Hr}{2\pi n} \tan\theta.$$

Hence, if H is known, the value of i can be obtained in terms of absolute units.

(c) *Difference of Potential*

Several types of electrometer, for the absolute determination of differences of potential, were designed by Thomson. One of his instruments, the *Quadrant Electrometer*,[1] consisted of a flat circular brass box divided into four quadrants (Fig. 52). A light aluminium needle was suspended within the quadrants and electrically charged. In some instruments Thomson used a bifilar suspension as a control for the movements of the needle; in other instruments he attached a small magnet to the needle, and used outside magnets to balance the deflections.

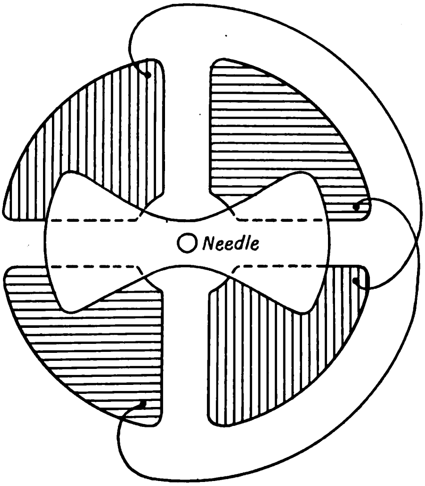

FIG. 52.—QUADRANT ELECTROMETER

One pair of quadrants was connected to the object whose potential was to be measured, and the other pair to the earth. The needle was thus acted upon by a deflecting couple due to the difference of potential between the quadrants, and by a restoring couple due to the particular method of control adopted. The deflection of the needle was read by the mirror and scale method, the instrument thus giving an accurate means for the detection and comparison of small differences of potential.[1]

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[1] *Papers on Electrostatics and Magnetism*, London, 1872, p. 262.

Another type of electrometer designed by Kelvin was known as the *Absolute Electrometer.*[2] It consisted of two parallel plates, one fixed and the other delicately mounted on a movable arm counterpoised at the other end. A weight was placed on the upper disc. The position of the disc with no difference of potential between the plates was recorded. When the difference of potential between two bodies was required, they were connected to the two discs and the weight removed. The lower disc was then moved by means of a micrometer screw until the electrical attraction brought it to its original position. In this position the attraction was equal to the weight originally on the disc. The distance between the discs was known, the area of the top plate could be measured and the difference of potential calculated from a simple formula deduced from theory. The 'attracted disc electrometer' thus gives a means for the calculation of a difference of potential in absolute units, that is to say, in terms of the fundamental units of mass, length and time. Lord Kelvin also devised a number of different pieces of apparatus for the absolute measurement of current. In these the attraction between two coils through which a current passed was 'weighed,' just as in the case of the attracted disc electrometer.

(*d*) *Resistance*

The first determination of resistance in absolute electromagnetic units was attempted in 1849 by Kirchoff (1824-1887). His method depends on the inductive action of one circuit on another. The two coils forming these circuits are joined to a galvanometer and battery. The wire of which the resistance is required forms a branch circuit in the system (Fig. 53). When the current is steady, there is a permanent deflection of the galvanometer. When the current in one of the coils is reversed, there is a kick of the galvanometer owing to the current induced in the other coil.

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[1] The theory of the instrument is given in Clerk Maxwell's *Treatise on Electricity and Magnetism*, 2nd edition, Oxford, 1881, vol. i. p. 311.

[2] *Papers on Electrostatics and Magnetism*, London, 1872, p. 281.

Denoting the current in the first coil by i, its rate of change by $\frac{di}{dt}$, then the induced electromotive force in the second coil is given by the formula, $-M\frac{di}{dt}$ (see p. 97), where M is called the coefficient of mutual induction of the two coils. This coefficient depends solely on certain geometrical relations between the coils. From a measurement of M by an independent experiment, and from the values of the two deflections, one for steady the other for transient currents, the value of the resistance can be calculated.

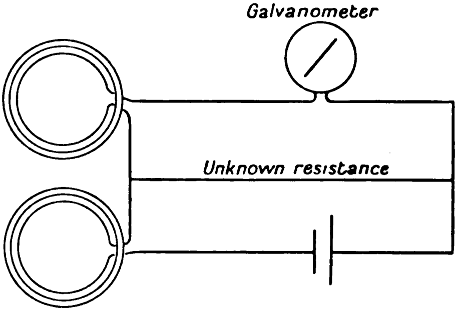

FIG. 53.—KIRCHHOFF'S CIRCUIT

Another method of absolute determination of resistance was introduced a few years later by Weber.[1] His method consisted essentially in revolving a large coil about a vertical axis in the magnetic field of the earth. In revolving, the coil cut through the lines of force of the earth's field, and an induced current was thus set up in the coil.

We have seen that the fundamental expression for an induced electromotive force is

$$e = -\frac{dN}{dt}.$$

Hence, if R is the resistance to be determined, and i the current, we have from Ohm's Law,

$$i = \frac{e}{R};$$

---

[1] Poggendorff's *Annalen*, lxxxii. p. 337 (1851).

and hence $$i = -\frac{1}{R} \cdot \frac{dN}{dt},$$

i.e. $$idt = -\frac{dN}{R};$$

but *idt* is the total quantity of electricity produced, and this can be found by a special type of instrument called a *ballistic galvanometer*. The value of *dN* depends upon the sum of the area of all the windings of the coil, on the rate at which it is rotated, and on the horizontal component of the earth's field.

From such considerations Weber was able to deduce an expression connecting the resistance with certain quantities he could measure. He was thus able to determine the resistance in absolute units.

§ 7. *Practical Units*

When instruments for the measurement of current, resistance and difference of potential in absolute units had been devised, the use of a universal absolute system of units became possible. The units, of course, depend on one another. We may summarize the connexion thus: A battery of which the electromotive force is unity will generate a current of unit strength in a wire of unit resistance and will convey unit quantity of electricity in unit time, and in doing so perform the unit of work. Now for practical purposes it is convenient to have for the unit of resistance (for example) the resistance of a definite quantity of some standard substance under stated conditions of temperature, etc. Consequently, after men of science in the different countries of Europe had agreed on an absolute system of units, it was still necessary to devise certain units for practical commercial purposes.

It was realized that the practical units should correspond as far as possible to certain well-known and easily-measured quantities and be reproducible in some simple concrete form. The standard of electromotive force, for instance, should be comparable with the electromotive force of a common form of voltaic cell such as the Daniell cell. The choice of the practical units was simply a matter of convenience. The electrical engineer and man of science demanded a system that would seldom involve any but simple numbers. Just as the currency of a country is rather inconvenient when it involves the payment of thousands of a certain unit for a tram fare, so the electrical engineer wanted practical units that would avoid constantly-occurring powers of ten in his ordinary computations.

The rapid development of telegraphy about the middle of the nineteenth century forced the problem of electrical units on the attention of men of science. The absolute unit of resistance was far too small for practical purposes. Makeshift units had been devised for immediate use. In England, for instance, the resistance of a mile of No. 16 copper wire was used as standard of resistance, while in Germany the German mile of No. 8 iron wire was selected. The British Association Committee of 1862 agreed to adopt a practical unit of 10^9 times greater than the absolute. This was first called the *Ohmad* and afterwards the *Ohm* in honour of that great physicist. The next thing to do was to measure practical standards such as certain coils of wire or columns of mercury in absolute measure, and hence by dividing by 10^9 to express such standards in ohms. Re-determinations of the standard ohm and the construction of standard ohm coils were made at different times; the most notable experiments were those of the late Lord Rayleigh in 1882-1883.

An International Congress on Electrical Units was held at Paris in 1881, and again at Chicago in 1893,[1] and standard units finally agreed upon. The international ohm was fixed at 10^9 C.G.S. units. It is represented by the resistance of a column of mercury of uniform cross-section, having a length of 106.300 cms. and weighing 14.4521 grammes at the temperature of melting ice. The practical unit of current, the international *ampere*, was defined as $\frac{1}{10}$th of the electro-magnetic unit. It is quoted as that current strength which deposits silver electrolytically at the rate of 0.001118 grammes per second. The practical unit of electromotive force, the international *volt*, was defined as that electromotive force which would produce a current of 1 ampere in a conductor of resistance 1 ohm.

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[1] British Association, *Report on Absolute Units*, London, 1913, p. 488. This is a forbidding volume of nearly 800 pages.

VII

DEVELOPMENT OF ELECTRICAL THEORY

§ 1. *Before Maxwell*

As knowledge of electrical phenomena became more widely diffused, the need became more and more pressing for the careful definition of terms. Therewith came important additions to the scientific vocabulary. This led to greater economy of words and the more ready interchange of ideas. Thus Poisson (see p. 38) introduced many conceptions now familiar to students of physics. Among these we may mention firstly *magnetic moment*, used to denote the product of pole strength and distance between the poles; and secondly *intensity of magnetization*, being the magnetic moment per unit volume.[1] Poisson introduced a function, representing the result obtained by adding all the electrical charges of a system, each divided by their distance from a given point. The work of Poisson was extended by the Cambridge mathematician, George Green (1793-1841), who gave the name *potential* to this function.[2] In the hands of Green the mathematical conception of potential became a powerful instrument whereby he established many theorems in electrostatics and magnetism. The work of Green, although published in 1828, was neglected until brought to light by Lord Kelvin in the early days of his career. Green's paper inspired much of the mathematical work of Lord Kelvin in electrostatics and magnetism. The potential at any point in the neighbourhood of an electrified body was afterwards defined by Lord Kelvin as the quantity of work that would be required to bring a unit of positive electricity from an infinite distance to that point.[1] The difference of potential between two points is thus measured by the work done in bringing the unit of positive electricity from the point at lower to the point at higher potential.

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[1] *Annales de Chimie*, 1824, xxv. p. 113; and *Mem. de l'Acad.* 1824, v. p. 247.

[2] *Essay on the Application of Mathematical Analysis to the Theories of Electricity and Magnetism*, Nottingham, 1828.

Lord Kelvin introduced many new terms, among which we may mention the word *permeability*, used to denote the ratio of the force between two magnetic poles with air as the medium to the force between the same poles the same distance apart with another substance as the medium. The term *permeability* used in magnetism is thus the analogue of *specific inductive capacity* used in electrostatics (see p. 143).

The first attempt to connect the phenomena of induced currents with those of electrostatics was made by Weber in 1848.[2] He supposed an electric current to consist in the movement of a series of positive and negative charges, the positive charges moving in one direction and the negative charges in the other direction. Thus he evolved an expression for the value of a current in terms of the quantity of these charges and their velocity. This expression when substituted in Ampère's equations for the attraction between current elements enabled Weber to establish a formula for the electrostatic repulsion or attraction between two charges. His treatment of currents as charges moving with a definite velocity is of great interest in the light of subsequent work on the electron (see p. 171). A very important contribution of Weber to electrical science was his determination, in collaboration with R. Kohlrausch (1809-1858), of the ratio between the electrostatic and electro-magnetic units.[3]

In the preceding chapter we indicated the method by which certain absolute determinations of electrical magnitudes may be reached. Thus by measuring the same electrical quantity first in electrostatic and then in electro-magnetic units, the ratio between the two systems of units could be found. The quantity measured by Weber and Kohlrausch was the charge of a Leyden jar. The capacity of the jar was first ascertained by comparison with that of a sphere of known radius, the potential difference between the coatings of the jar being measured by an electrometer. The value of the charge in electro-magnetic units was estimated by measuring the transient current produced when the jar was discharged through a galvanometer. The ratio of the electro-magnetic to the electrostatic unit thus determined was found to be numerically the same as the velocity of light. This amazing conclusion seemed at the time wholly inexplicable, but was confirmed by subsequent determinations by other methods. No complete interpretation of this result was forthcoming until the investigations of Maxwell.

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[1] *Papers on Electrostatics and Magnetism*, London, 1872, p. 87.

[2] *Ann. d. Phys.* lxxiii, 1848, p. 193. English translation in Richard Taylor, *Scientific Memoirs*, London, 1852, vol. v. p. 510.

[3] Pogg. *Ann.* xcix, 1856, p. 10.

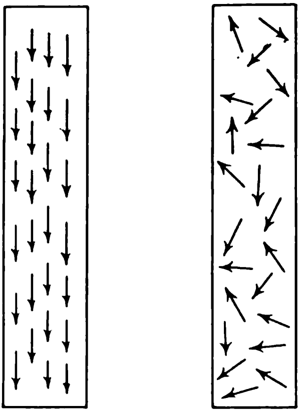
Fig. 54.—Illustrating Weber's Molecular Theory

The name of Weber is always associated with the molecular theory of magnetism.[1] He attempted to use Ampère's hypothesis of molecular currents to interpret magnetic phenomena, and was especially interested in the phenomena of diamagnetism observed by Faraday (see p. 101). Weber regarded the molecules of a substance such as iron as little magnets. In the unmagnetized state he supposed the axes of these molecular magnets to lie in every possible direction. An outside magnetizing force, however, tends to turn the axes of these little magnets in one direction. When this happens, adjacent north and south poles neutralize one another so that the piece of iron exhibits polarity at the ends only (Fig. 54). If the molecular magnets could rotate freely, the smallest magnetizing force would suffice for complete magnetization. But this, as we know, is not the case. Weber, therefore, had to suppose that there is some directive force tending to retain the little magnets in their original positions. An important simplification of this 'molecular view' was made by Ewing in 1890.[1] He showed that the mutual interaction of the molecular magnets themselves acts as a controlling force. Thus Ewing satisfactorily accounted for magnetic saturation and allied phenomena.

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[1] *Ann. d. Phys.* lxxiii, 1848, p. 241. Richard Taylor, *Scientific Memoirs*, London, 1852, v. p. 477.

A characteristic of the English, and more particularly of the Cambridge School of physicists, is the devising of mechanical models to illustrate physical phenomena. Lord Kelvin possessed great capacity in this respect. One of his earliest papers contained a mathematical treatment of electrostatic phenomena by a comparison with those of elasticity. It had long been known that a charged body could induce an opposite charge on another or affect an electroscope nearby. As we have seen, various hypotheses were put forward to account for this. Kelvin, knowing that a stress can be propagated through an elastic solid, pictured the propagation of electric force as taking place in a similar manner. His scientific activity was enormous, and he always had so many preoccupations that he did not at the time pursue this conception further. Meanwhile, the problem was attacked in a masterly manner by another Cambridge physicist, Clerk Maxwell.

§ 2. *Clerk Maxwell*

James Clerk Maxwell was born at Edinburgh in 1831. He was educated at Edinburgh Academy and for a time at the University of that city. From the age of twelve he had a taste for versification. His schoolboy letters showed a growing interest in mathematical and scientific studies, often expressed in serio-comic poems and mingled with descriptions of the delights of out-door games.[2] In mathematics he showed a remarkable precocity which foretold his maturer genius. Even when quite a young boy, his father used to take him to meetings of the Edinburgh Royal Society. He studied Conics at the age of fourteen, and actually contributed original papers on curve-tracing to the Edinburgh Royal Society at that age.[1] Although his obvious bent was towards Mathematics, Maxwell kept to the ordinary school curriculum, which devoted great attention to classics and literature. His health was never good and he had frequent absences from school during the trying Scottish winters. When unable to attend the meetings of the learned societies, the 'Wise Men,' as he called them, he eagerly absorbed from his father news of the proceedings, especially of those dealing with magnetism and light.

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[1] *Proc. Roy. Soc.* vol. 48, 1890, 342; and *Phil. Mag.* xxx, 1890, p. 205.

[2] *Life of James Clerk Maxwell*, Campbell and Garnett, London, 1884.

At Cambridge Maxwell studied Mathematics first at Peterhouse, then at Trinity. At twenty-two he became Second Wrangler, and was declared equal with the Senior Wrangler in the examination for the Smith's Prize. Elected immediately as a Fellow of Trinity he had leisure for experimental work. He applied himself at once to his favourite study of Optics and Colour Vision, and exhibited a Colour Top before the Cambridge Philosophical Society. A year later he wrote to his father:

> 'I am reading Electricity and working at Fluid Motion, and have been working my way into the views of heavy German writers. It takes a long time to reduce to order all the notions one gets from these men, but I hope to see my way through the subject and arrive at something intelligible in the way of a theory.'

Maxwell was also studying the work of Faraday, and thus gathering material for his own great contributions to electrical theory.

Maxwell was Professor of Natural Philosophy at Aberdeen for a time, and then for eight years he held the chair of the same subject at King's College, London. His duties in London were very exacting, for in addition to the nine months' session there were evening lectures to working men and considerable work in

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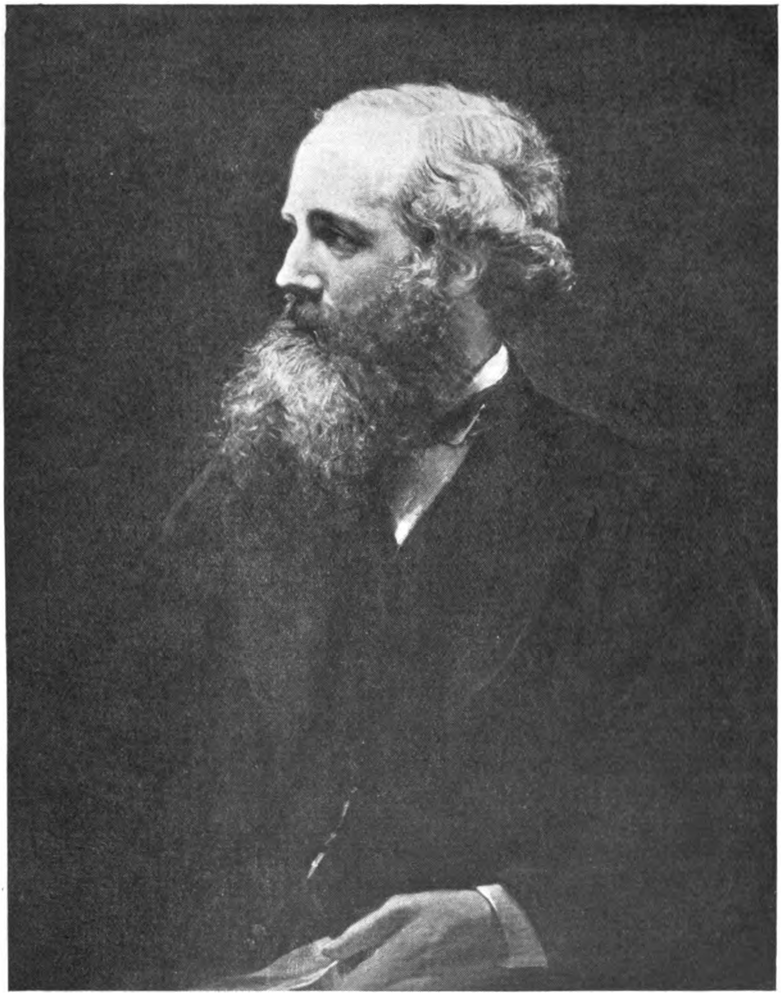
[1] 'On the Description of Oval Curves and those having a Plurality of Foci,' by Mr. Clerk Maxwell, Junior. *Proc. Edin. Royal Society*, vol. ii. pp. 89-93.



James Clerk Maxwell

connection with examinations. He carried out some experimental investigations in his house at Kensington, and while in London he was privileged by intercourse with Faraday, for whom he had the deepest admiration. Faraday was now living in retirement at Hampton Court, and the two men had many an interesting talk together.

The determination of electrical standards had been suggested by the British Association Committee in 1862. Experiments to that end were commenced at King's College under the direction of Maxwell. Twice during his sojourn in London he suffered from severe illness, and it was mainly owing to ill-health that he resigned his post and retired for a time to his Scottish estate. During this interlude of peace he worked at his great *Treatise on Electricity and Magnetism*. This work served to systematize electrical and magnetic theory in a manner never before attempted. Maxwell was soon called from his retirement to the newly-founded Chair of Experimental Physics at Cambridge. By a Grace of the Senate of 9th February, 1871, it was enacted that the principal duty of the professor should be to

> 'teach and illustrate the laws of Heat, Electricity and Magnetism; to apply himself to the advancement of the knowledge of such subjects, and to promote their study in the University.'

After much persuasion from his friends, the position was accepted by Maxwell.

For some time after his appointment he had to devote his whole attention to the building and equipment of the Cavendish Laboratory. He threw himself with characteristic energy into his new work. In dealing with students the influence of his great personality must have been incalculable. Some of his admirers have, however, regretted the inroads made by teaching and organisation on the few years of his life, which, in their opinion, should have been wholly devoted to that creative work in which he stood alone. While the furnishing of the laboratory was in progress, Maxwell gave courses of lectures on prescribed subjects. For those able to follow his rapid changes of thought, his lectures must have been a source of inspiration and delight.

Literary labours also made claims upon him. At the suggestion of Lord Kelvin, Maxwell undertook the preparation of Cavendish's manuscripts for publication. A great deal of labour was required, and it was five years before the work was finished. Maxwell repeated many of Cavendish's experiments, notably those on the conductivity of different liquids, so that long-suffering students had to submit themselves to shocks in order to make themselves into galvanometers, just as Cavendish had done ! Maxwell loved a joke, and his happy, playful spirit often expressed itself in verse.[1]

Five years after his appointment to the Cavendish Chair, Maxwell was again troubled by ill-health, but this time its nature was more grave. His friends noticed a falling off in his usual gaiety and abundant energy, though he continued to visit the laboratory daily until the spring of 1879. The summer months were spent in Scotland, but he grew weaker, and in the autumn, on his return to Cambridge, his strength gradually failed. On 5th November he passed away. Of noble and beautiful character, he possessed that homogeneity of mind best described by the old-fashioned phrase : 'singleness of heart.'

There is a unique aesthetic quality in his work that makes us always look with reverence from Maxwell the physicist to Maxwell the man. His work placed him in the first rank of investigators of all ages, and his death at the early age of forty-eight was an irreparable loss.

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[1] The following stanza is taken from an amusing parody he wrote on Tennyson's 'Blow Bugle, Blow.'

Place : A small alcove with dark curtains.
Subject : Thomson's mirror galvanometer.

'The lamplight falls on blackened walls
And streams through narrow perforations,
The long beam trails o'er pasteboard scales,
With long-decaying oscillations.
Flow, current, flow, set the quick light spot flying,
Flow current, answer light spot, flashing, quivering, dying.'

§ 3. *Maxwell's Conception of the Electro-magnetic Field*

Soon after taking his degree at Cambridge, Maxwell read a paper *On the Transformation of Surfaces by Bending,* and later a memoir *On Faraday's Lines of Force.* He obtained the Adam's Prize for an essay *On the Stability of Saturn's Rings,* and was awarded the Rumford Medal by the Royal Society for his investigations on Colour and Colour Vision. He carried out very important investigations on the Kinetic Theory of Gases, and wrote a text-book on the *Theory of Heat* (1871) and an elementary treatise on *Matter and Motion* (1876). These instances well illustrate his versatility. His greatest work was, however, devoted to electricity. While an undergraduate at Cambridge he had read Faraday's *Experimental Researches.* He possessed a power of visualizing like to that of Faraday, but in addition had mathematical genius carefully developed by training. His first contributions to electrical theory amounted to a translation of some of Faraday's ideas into mathematical language. Like Faraday, he abandoned the notion of action at a distance, and sought to interpret electrical and magnetic phenomena in terms of stresses in the medium through which the action passed. His important contributions to electrical science appeared in four famous memoirs.

In his first memoir Maxwell begins by drawing attention to the familiar experiment of sprinkling iron filings near the poles of a magnet.

> 'The beautiful illustration of the presence of magnetic force,' he says, 'afforded by this experiment naturally tends to make us think of the lines of force as something real, and as indicating something more than the mere resultant of two forces whose seat of action is at a distance. . . . We cannot help thinking that in every place where we find these lines of force, some physical state or action must exist in sufficient energy to produce the actual phenomena. My object in this paper is to clear the way for speculation in this direction by investigating the mechanical results of certain states of tension and motion in a medium and comparing these with the observed phenomena of magnetism and electricity.'[1]

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[1] 'On Physical Lines of Force,' *Phil. Mag.* xxi, 1861, p. 161.

He supposes that the phenomena of *magnetism* are due to a tension along the lines of force together with a pressure at right angles to them. In seeking a mechanical explanation of such a state, he supposes that the pressure at right angles to the lines of force arises from the centrifugal force of vortices or eddies having their axes in directions parallel to these lines. From this hypothesis of molecular vortices, Maxwell was able to give a mechanical explanation of the force acting on a north or south pole placed in a magnetic field.

In his second electrical paper, Maxwell says :

> 'We have as yet given no answers to the questions : " How are these vortices set in rotation ? " and " Why are they arranged according to the known laws of force about magnets or currents ? " . . . We have, in fact, now to enquire into the physical connection of these vortices with electrical currents, while we are still in doubt as to the nature of electricity, whether it is one substance, two substances, or not a substance at all, or in what way it differs from matter, and how it is connected with it.' [1]

Although Maxwell possessed abundant powers of abstraction, yet he liked to see how things worked, and so was accustomed to devise mechanical models to illustrate his conclusions. He naturally found it difficult to imagine vortices revolving side by side about parallel axes, for this would require adjacent portions of the medium to be moving in opposite directions. Consequently, he pictured a layer of particles each revolving on its own axis in a direction opposite to that of the vortices, just as in the familiar arrangement of an idle wheel placed between two other wheels with which it is in gear.

Maxwell conceived an electric current as represented by a transference in a definite direction of these movable particles between neighbouring vortices (Fig. 55). In the figure, the large spaces represent vortices and the small circles the layer of particles between them, which, by hypothesis, represent electricity. If a current flows in the direction *A.B.*, the row of vortices *g.h.* will be set in motion in a counter clock-wise or positive direction. Supposing the row of vortices *k.l.* to be still at rest, then the layer of particles between these rows will be acted on by the row *g.h.* from beneath and will be at rest above. If free to move, these particles will therefore rotate in the clock-wise or negative direction, and will move from right to left. This movement will be in a direction opposite to that of the original current, and it will so form an induced current. Maxwell thus conceives the phenomena of *induced currents* to be due to the communication of the rotational velocity of the vortices from one part of the field to another.

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[1] *Phil. Mag.* 1861, p. 282.

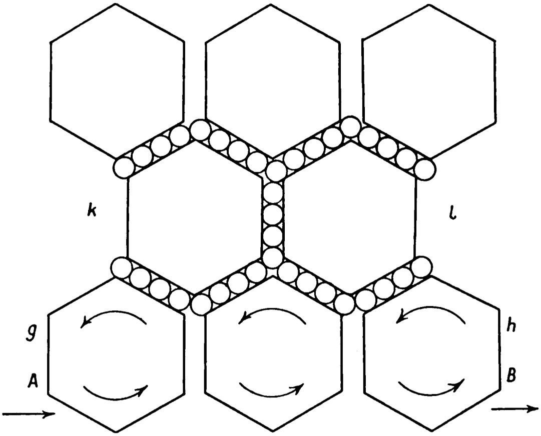

FIG. 55.—ILLUSTRATING MAXWELL'S VORTICES

In his third electrical memoir, Maxwell shows how the conception of molecular vortices may be used to interpret the phenomena of *electrostatics*.[1] The rotating matter he conceives as before in the form of vortices or eddies. The tangential force by which the particles between the vortices are pressed together, he conceives as electromotive force. The pressure of the particles on each other he conceives as corresponding to the tension or potential of the electricity. The state of the medium when the electric particles are displaced in a definite direction, he considers to represent the electrostatic field. The displacement itself when it has attained a certain value remains constant, showing itself as a state of tension, but variations in the displacement he regards as currents. Maxwell thus considers the electrostatic state as due to the displacement of something from its position of equilibrium, and that the movement of this 'something' constitutes what he calls a *displacement current.* Any changing displacement he considers as an electric current, even when there is no material conductor present. This *displacement current* is a unique feature of Maxwell's theory.

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[1] 'The Theory of Vortices applied to Statical Electricity,' *Phil. Mag.* 1862, p. 12 ; and see his *Treatise on Electricity and Magnetism*, 3rd edn., Oxford, 1892, vol. ii. p. 468.

§ 4. *The Electro-magnetic Theory of Light*

Maxwell's fourth important electrical paper[1] was a very extensive memoir which appeared in 1865. In it the conceptions and mathematical deductions of his previous communications were given in a more developed form. The hypothesis of molecular vortices with layers of particles between enabled Maxwell to treat electrical phenomena from the dynamical point of view. Thus, in his theory, we find the expressions *energy* of an electric current, *elasticity* of the medium, and *momentum* of the varying electro-magnetic field.[2]

We have seen that when a circuit is broken, the current does not instantly cease, but persists for a very short time. In other words, an electric current, like a material body, requires a good push to start it moving, but when once the inertia has been overcome and it has acquired momentum, it resists being stopped. Maxwell, in considering the effects of self-induction, was thus led to think of an electric current as having kinship to the momentum of a moving body. The heating effect of a current and the definite relationship between heat and work had familiarized physicists with the notion of electrical energy. Maxwell, however, went further. He pictured all the phenomena of an electric current as those of a moving system, the motion being transmitted from one part of the system to another by forces subject to the usual dynamical laws. The hypothesis of *displacement currents*, *i.e.* of currents in an insulating medium, had broken down the barrier between electrostatic and electrokinetic phenomena, so that Maxwell had reduced the two complex problems to one.

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[1] 'A Dynamical Theory of the Electro-magnetic Field,' *Phil. Trans.* 1865, p. 459.

[2] *Ibid.*, p. 645.

In the subsequent mathematical part of his memoir he develops twenty equations involving twenty variables. Of these we may note the following:

a. The relation between electric displacement, true conduction and the total current compounded of both.
b. The relation between the lines of magnetic force and the inductive coefficients of a circuit, as already deduced from the laws of induction.
c. The relation between the strength of a current and its magnetic effects, according to the electro-magnetic system of measurement.
d. The value of the electromotive force in a body, as arising from the motion of the body in the field, the alterations of the field itself, and the variations of electric potential from one part of the field to another.
e. The relation between an electric current and the electromotive force which produces it.
g. The relation between the amount of free electricity at any point, and the electric displacements in the neighbourhood.

By combining these equations Maxwell obtained a simple expression for the repulsion between two electrified bodies in electro-dynamic units. If e_1, e_2 are the charges and r the distance between them, the force was given by the formula

$$\frac{k}{4\pi} \cdot \frac{e_1 e_2}{r^2},$$

k being the specific inductive capacity of the medium (see p. 143).

But from the law of inverse squares the force is $\frac{\eta_1 \eta_2}{r^2}$, where $\eta_1 \eta_2$ are the charges in electrostatic units.

Now if v represent the ratio between the electro-magnetic and electrostatic units, it follows that

$$\eta_1 = v e_1,$$

$$\eta_2 = v e_2,$$

whence $$\frac{v^2e_1e_2}{r^2}=\frac{k}{4\pi}\frac{e_1e_2}{r^2};$$

i.e. $$k=4\pi v^2,$$

or $$v=\pm\sqrt{\frac{k}{4\pi}}$$

This ratio between the units had been found from the experiments of Weber, Kohlrausch (see p. 124) and others to be numerically equal to the velocity of light.

We have seen how Maxwell in his investigation of electro-magnetic phenomena sought an interpretation in terms of the properties of the insulating medium. Now it happens that in the Wave Theory of Light it is necessary to posit a medium or ether, and to endow it with certain properties in order to interpret the phenomena of refraction, polarization, etc. Maxwell pointed out that it is unphilosophical to fill space with another kind of ether every time a new phenomenon has to be explained. It seemed reasonable to him that the same medium required for the Wave Theory of Light should also serve for the explanation of electro-magnetic effects.

Maxwell therefore turned once more to his equations. Assuming that an electro-magnetic disturbance is propagated through the field by means of a plane wave, that is, a wave in which the electric intensity is the same at any instant over the whole plane, he obtained a simple expression for the velocity of such a wave. If V denote the velocity of the wave, k the specific inductive capacity as before, and μ the permeability of the medium (see p. 123), Maxwell found that

$$V=\pm\sqrt{\frac{k}{4\pi\mu}};$$

but he had already shown that

$$v=\pm\sqrt{\frac{k}{4\pi}},$$

where v is the ratio of the electro-magnetic to the electrostatic units.

Now, since the only medium in which experiments have been made for values of k is air, for which $\mu = 1$, he could write

$$V = \pm\sqrt{\frac{k}{4\pi}}.$$

Hence $$V = v,$$

i.e. the velocity of propagation of the wave is equal to the ratio v between the units, and this by experiment is numerically equal to that of light.

Thus Maxwell by purely theoretical investigations deduced that an electro-magnetic disturbance travels with the velocity of light. What more reasonable inference than that light itself is an electro-magnetic phenomenon? Maxwell extended his theory to account for the propagation of light in crystals and other media, but with this aspect of his work we are not occupied. From the electro-magnetic theory, however, Maxwell showed that a periodic *electrical* disturbance, which in its turn gives rise to a periodic *magnetic* disturbance, should travel with a wave-motion the velocity of which should be the same as that of light. During Maxwell's time it was realized that the ratio of the electro-magnetic to the electrostatic unit has the *dimensions* of a velocity. This consideration lent some support to Maxwell's views from the purely theoretical side of the subject. But ten years after Maxwell's death electro-magnetic waves were actually detected, their velocity calculated, and the results of experiment found to agree with the *predictions* of his theory. The achievement by which mathematical analysis led to results identical with those deduced from observations, and the results thus deduced found to be identical with results in an entirely different department, is surely among the most remarkable in the whole history of science.

§ 5. *The Successors of Maxwell*

The Electro-magnetic Theory of Light was a shock to the sensibilities of some of the more conservative physicists, who were reluctant to abandon the obliging elastic solid ether which had served them so long and so faithfully. Lord Kelvin in particular was unwilling to accept the newer views. But Maxwell's investigations brought about a great simplification in electrical theory. His *Treatise on Electricity and Magnetism*, published in 1873, is a landmark in the history of science. The wide and philosophical outlook evident throughout the whole work, despite the difficulties of the mathematical exposition, has remained a source of inspiration to all workers in physical science.

But for some years there was no experimental evidence for the existence of electro-magnetic waves. Lord Kelvin had shown mathematically the conditions for the oscillatory discharge of a Leyden jar. Helmholtz had referred to such oscillations of electric intensity in his great essay on the conservation of force. But until the work of Maxwell, electric disturbance was not regarded as a wave motion propagated with a finite velocity. Helmholtz suggested to one of his pupils, Heinrich Hertz (1857-1894), the practical investigation of electric oscillations with a view to verifying experimentally the results of Maxwell.

After several early attempts, Hertz in 1888 demonstrated the existence of electro-magnetic waves in the space surrounding a discharging Leyden jar.[1] In his later experiments Hertz used an induction coil joined to two sheets of metal attached to rods, at the ends of which were two polished metal balls (Fig. 56). When the induction coil was in action with a sufficient difference of potential a spark passed between the metal balls, and an oscillatory discharge took place between the metal sheets. To detect the electro-magnetic radiation, Hertz employed a circular conductor provided with small gap. When this detector was held in certain positions, sparks were observed to pass across the gap.

Having convinced himself that the oscillations set up by the induction coil are propagated into the space around, Hertz proceeded to a determination of their velocity. His experiments and calculation were complicated, but the method consisted essentially in transmitting the oscillations to the detector by two paths, one along a connecting wire, and the other through the air. He adjusted the apparatus until the two effects produced interference, and hence calculated the ratio of the two velocities. The velocity of propagation in the connecting wire was calculated from the frequency of the original oscillations and from the wave-length of the disturbance in the wire. The value of the velocity in the air was found to be of the order of that of light. Here at last was the confirmation of Maxwell's prediction.

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[1] *Nature*, 39, 1889, pp. 402, 450, 547.

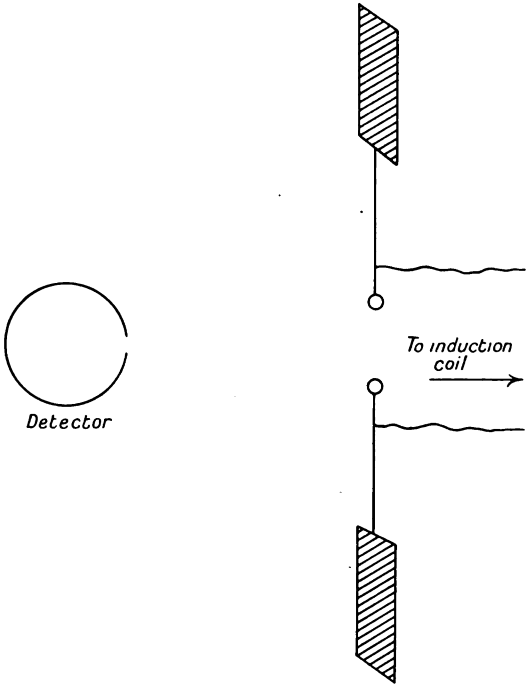

FIG. 56.—ONE FORM OF OSCILLATOR AND DETECTOR USED BY HERTZ

The forms of oscillators and detectors used by Hertz were improved by Lodge,[1] who made many important contributions to the study of electro-magnetic waves. The work of Hertz and Lodge has been followed by the application of such waves to signalling, that is to *Wireless Telegraphy*. The practical use of such waves has been due largely to the labours of Marconi and of Fleming.[1] One of the simplest forms of circuit for the transmission of electro-magnetic waves consists of an induction coil coupled to a condenser and transformer (Fig. 57). One winding of the transformer is joined to the induction coil, the other to a long vertical conductor or *aerial*. The virtual length of the aerial can be adjusted so that electro-magnetic waves of sufficient intensity are radiated in all directions. At the receiving station the electro-magnetic waves meet a tuned aerial, where rapidly oscillating induced currents are set up. These induced currents, after being *rectified* by crystal or valve, are, as it were, translated into sound in the telephone which fits comfortably over the listener's head.

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[1] *Nature*, 41, 1890, p. 368.

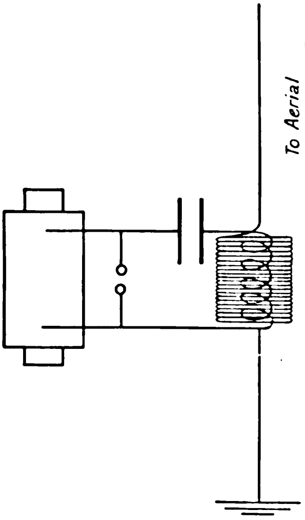

FIG. 57.—SIMPLE CIRCUIT for the transmission of electro-magnetic waves

Signalling by 'wireless' has been adopted throughout the civilized world, and within recent years the 'broadcasting' of news and concerts has become so familiar that it will soon cease to excite wonder. The misleading antithesis between theory and practice sometimes leads to the unfortunate conclusion that technical inventions and practical applications are the sole justification for the labours of the man of science. Practice is thus considered to be worth more than theory. But the search for knowledge is its own reward. If it leads to applications of benefit to mankind, well and good: if not, it is still worth while. The evolution of Wireless Telegraphy affords an example of the application of the work of one who laboured for knowledge alone, one who was a supreme theorist, a visionary and a dreamer.

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[1] J. A. Fleming, *The Principles of Electric Wave Telegraphy and Telephony*. London, 1920.

VIII

ELECTROLYSIS

§ 1. *Faraday's Laws*

AFTER the completion of his experiments on electro-magnetic induction, Faraday once more took up the subject that had interested him in the early days of his work under Davy—the study of the voltaic pile and electrolytic decompositions. It was supposed, at the time, that the decomposition of a solution was brought about by the attraction of the metallic terminals at the point at which the current enters or leaves the liquid. We have seen how Grothuss and Davy pictured a chain of decompositions in the space between the terminals (p. 50). De la Rive of Geneva [1] made the alternative suggestion that only the molecules near the terminals were actually split up, and that the parts of the broken-up molecules actually travel through the solution from one pole to another.

In order to test whether the contact of the metallic terminals actually brings about chemical decomposition, Faraday moistened some paper with a solution of a salt and fixed it on insulating supports between the knobs of an electrical machine.[2] He arranged that the knobs should be separated from the paper by short air gaps. On working the machine he found that the salt solution was decomposed. He therefore concluded that contact of the metal terminals is not essential for decomposition.[3]

To Faraday we owe the terms universally employed in describing electro-chemical decompositions. Thus the terminals by which the current enters or leaves a solution he called *electrodes*, that by which the current enters he called the *anode*, the other the *cathode*. Solutions decomposed by a current he called *electrolytes*, and the split-up parts of the molecules he called *ions*.[1]

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[1] *Annales de Chimie*, 1825, xxviii. p. 190.

[2] *Exp. Researches*, § 450.

[3] *Ibid.*, § 523.

The quantitative investigations of Faraday on electrolytes led him in 1833 to enunciate the following results:

1. The mass of the product liberated is proportional to the quantity of electricity passed through the electrolyte.
2. When the same current is passed through different electrolytes, the masses of the liberated products are in the ratio of their chemical equivalents (Fig. 58).

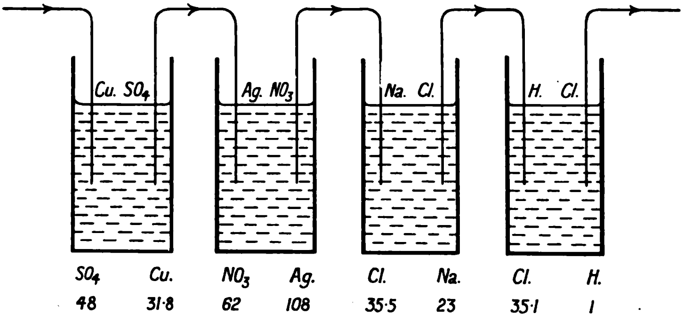

FIG. 58.—ILLUSTRATING FARADAY'S SECOND LAW OF ELECTROLYSIS

All the subsequent quantitative work on the conduction of electricity through liquids was based on these two generalisations now known as Faraday's Laws. Faraday himself realized the significance of the second law in linking up electrical and chemical phenomena. He showed how this law leads to the conclusion that there is a certain definite electrical charge associated with the atom, since the quantity of electricity passed through the electrolyte may be regarded as equivalent to the quantity originally possessed by the atoms afterwards liberated at the electrodes. This point is of great importance in both electrical and chemical theory, and we may well quote Faraday's views on it.[2]

> 'The atoms of matter are in some way associated or endowed with electrical powers, to which they owe their most striking

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[1] Greek—wanderers or travellers.

[2] *Exp. Researches*, 1833, §§ 852, 869.

> qualities, and amongst them their mutual chemical affinity. . . . The harmony which [this view] introduces into the associated theories of definite proportions and electric chemical affinity is very great. According to it, the equivalent weights of bodies are simply those quantities of them which contain equal quantities of electricity, or have naturally equal electric powers; it being the *electricity* which determines the equivalent number, because it determines the combining force. Or, if we adopt the atomic theory or phraseology, then the atoms of bodies which are equivalent to each other in their ordinary chemical action, have *equal quantities of electricity naturally associated with them.* But I confess I am jealous of the term *atom*; for though it is very easy to talk of atoms, it is very difficult to form a clear idea of their nature, especially when compound bodies are under consideration.'

Thus Faraday, writing in 1833, pictured to himself a natural unit or 'atom' of electricity associated with the atoms of matter.

Indeed, his researches afforded the first experimental evidence in favour of an atomic view of electricity: yet, from the passage quoted above, we see that he was rather afraid of the term atom. Now his other investigations in electricity called attention to the medium as a means for the transmission of electrical effects, and this conception, developed mathematically by Clerk Maxwell, dominated electrical theory for many years. We may regard Faraday's views on the equal quantity of electricity naturally associated with the atoms of matter, as prophetic. Not until fifty years later were other physicists bold enough to suggest the discrete or atomic nature of electricity.

Faraday's investigations of the passage of a current through solutions of salts led him to experiment with other substances, such as sulphur and turpentine.[1] He found that although these substances do not conduct a current, yet they affect the capacity of a condenser. By measuring the capacity of condensers first with air between the plates and afterwards with the insulating substance such as sulphur between the plates, Faraday obtained a constant which he called the *specific inductive capacity* of the insulating substance. Such constants had been obtained by

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[1] *Exp. Res.* 1837, § 1252.

Cavendish (p. 33) many years before, but his results had not yet been published. Faraday's discovery of this property of insulating substances had an important bearing on the subsequent electro-magnetic theory of Clerk Maxwell.

§ 2. *Electrolytic Dissociation*

When the significance of Faraday's Laws of Electrolysis was realized, further objections were found to the hypothesis of Grothuss and of Davy that electrolysis was brought about by a chain of decompositions that passed through the electrolyte. If the views of Grothuss and of Davy were accepted, and if, with them, we were to suppose that the force of the current dissociates the molecules and sets them in motion, then doubling the current should both double the number of molecules existing at any one time and also double their velocity. This would mean that the mass of the deposited product in any given time would be four times the original value. Faraday had shown, however, that the mass deposited is directly proportional to the product of current strength and time. Again it might be supposed that to bring about the initial splitting of the molecules, a definite electromotive force would be required in order to form at least a single chain of dissociated molecules. Below this value no electrolysis could take place. It was, however, shown experimentally that the strength of the applied electromotive force could be indefinitely reduced without decomposition ceasing in solutions of metallic salts.

A fruitful suggestion as to the state of compounds in solution was put forward by the English chemist, Alexander Williamson (1824-1904), of University College, London. In 1850,[1] in the course of an account of his theory of the formation of ethyl ether, he supposed that decompositions and re-combinations of the molecules are continually taking place in a solution. Williamson used this idea of alternate formation and decomposition of molecules to explain certain chemical phenomena.

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[1] *Phil. Mag.* xxxvii, 1850, p. 350.

Quite independently of Williamson, however, the same idea was suggested by Clausius of Zürich in 1857, and formed the starting-point of his theory of electrolysis.[1] The dissociated parts of the electrolyte Clausius calls *partial molecules*. These, he assumes, carry opposite electric charges. He supposes that decompositions and re-combinations occur throughout the entire mass of the liquid. Thus the number of positive partial molecules reaching the cathode in a given time is the same as the number of negative partial molecules leaving the anode, although the individual dissociated positive and negative partial molecules thus deposited were not, in fact, originally united in the solution. He then draws attention to the important fact that Ohm's Law holds for solutions, and that therefore any hypothesis which assumes that the molecules are actually split up by the force of the current must be abandoned. Clausius assumes rather that the applied electromotive force simply causes a *drift* of *partial molecules* (or *ions*, to adopt Faraday's term) of one kind towards the anode and of the other kind towards the cathode. It is this drift that constitutes the current in the solution.

In his views on electrolysis he supposes that the frequency of the mutual decompositions going on depends on the molecular motion, *i.e.* on the temperature.[2] He points out, too, that the fact that increase in the conductibility of electrolytes follows from an increase in temperature, supports his view that molecular motions are the vehicle for the transmission of electricity through liquids.

The work of Faraday on electrolysis had been the inspiration for a number of investigations in England. Some experiments [3] on the changes of concentration noticed during electrolysis were performed by Frederick Daniell (1790-1845), Professor of

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[1] 'On the Conduction of Electricity in Electrolytes,' *Phil. Mag.* xv, 1858, p. 94.

[2] 'On the Nature of the Motion which we call Heat,' *Phil. Mag.* xiv. p. 113.

[3] 'Additional Researches on the Electrolysis of Secondary Compounds,' *Phil. Trans.* 1844, p. 1.

Chemistry at King's College. Daniell arranged a porous partition in the vessel in which electrolysis was carried on, and tested the concentration of the liquid in the neighbourhood of the electrodes. He examined the electrolysis of a great number of compounds, and came to the conclusion that in many cases the current is carried chiefly by the *anion*, and that the *anion* and *cation* travel with different velocities. Investigators had long been troubled with the effect of what is called polarization. It had been known, even in the early days of the voltaic cell, that after a cell has been in use for some time its electromotive force decreases. This decrease is due to certain chemical changes confined to the surfaces of the electrodes, and are usually caused by the accumulation of hydrogen on the copper or silver plate. The ordinary chemical cells such as those of Grove, Bunsen and Leclanché were all devised to avoid this polarization effect by changing the hydrogen to water by means of a suitable oxidizing agent. In the well-known cell designed by Daniell in 1836, and since called after him, the zinc plate is immersed in sulphuric acid in a porous pot (Fig. 59). This pot stands inside a copper vessel which forms the positive plate of the cell, the electrolyte outside the porous pot being copper sulphate solution. The hydrogen in travelling towards the copper reacts with the copper sulphate so that copper is deposited on the inside of the copper pot. Thus the nature of the positive plate is unaltered, and hence there is no polarization. Until the introduction of dynamo-electric machinery on an extensive scale, batteries of Daniell cells were the only means of obtaining a constant electromotive force.

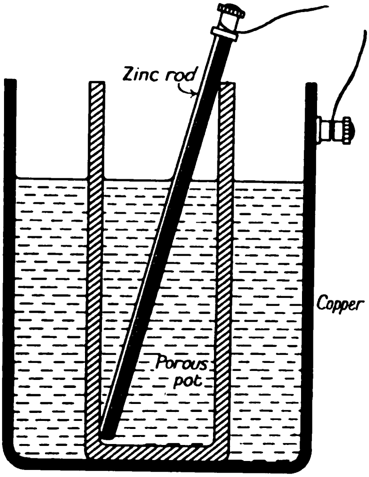

FIG. 59.—DANIELL'S CELL

§ 3. *Measurement of the Velocities of Ions*

This conception of the differing velocities of the anion and cation suggested by Daniell was taken up by Hittorf [1] of Münster. Hittorf considered that the changes in concentration of the solution near the electrodes is due to the differing velocities of anion and cation. If the anion travels the faster, the end of the solution from which it comes will become more dilute than the end towards which it travels. Hittorf measured by chemical means the concentration of the solution near the electrodes, and the ratio of the changes in concentration occurring during the electrolysis gave him the ratio of the ionic velocities.

The problem of ionic velocities was also taken up by F. W. Kohlrausch [2] of Würtzberg (1840-1910), and his investigation marks an important advance in the subject. His results, which were made known in 1876 and 1877, gave the means for an experimental determination of the absolute velocities of ions. Kohlrausch showed beyond doubt that where polarization does not occur, Ohm's Law holds for electrolytes as for metallic conductors.

Kohlrausch avoided the effects of polarization by employing an alternating current. He used a modification of the Wheatstone Bridge method for finding the resistance, substituting a telephone for a galvanometer. This change was necessary because a rapidly alternating current would have had no effect on a galvanometer. The resistances in the arms of the bridge are so adjusted that the sound in the telephone is at a minimum on attaining the requisite balance (Fig. 60).

Kohlrausch found that the conductivity of a solution increases up to a certain limit as the solution becomes more and more dilute. This limit he regarded as the state in which the maximum ionisation had taken place. It was this conception which enabled him to form an estimate of ionic velocities. He could regard a solution simply as a conductor to which Ohm's Law might be applied. Again, from Faraday's second law it follows that each *gramme equivalent,* that is the equivalent weight expressed in grammes, carries the same electrical charge. Denoting this charge by E, the velocities of anion and cation under unit fall of potential per centimetre by v and u, and the gramme equivalent by m, the current conveyed through every cubic centimetre is $mE(u+v)$. If we denote the conductivity by k, it follows that since the fall of potential is unity, the current per cm. $=k$. $\therefore\ k=mE(u+v)$. Kohlrausch used the symbol λ to denote the value of the ratio $\frac{k}{m}$ at infinite dilution, *i.e.* when the conductivity is a maximum. Hence we may write

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[1] 'Über die Wanderungen der Ionen während der Elektrolyse,' *Ann. d. Phys.* lxxxix, 1853, p. 177.

[2] *Ann. d. Phys.* vi, 1879, pp. 1, 145.

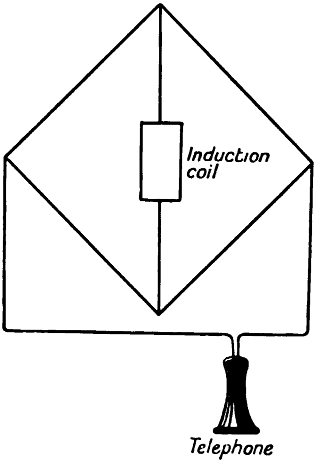

FIG. 60.—MODIFIED FORM OF WHEATSTONE'S BRIDGE USED BY KOHLRAUSCH

$$k=m\lambda.$$

But
$$k=mE(u+v).$$

Hence
$$m\lambda=mE(u+v),$$

or
$$\lambda=E(u+v).$$

The value of E is known from other considerations, and since λ can be found experimentally, $(u+v)$ can be calculated. Now the ratio u/v can be found by Hittorf's method, and so the absolute values of u and v can be determined.

§ 4. *The Ionic Theory of Arrhenius*

An investigator whose work had important though indirect influence on the course of electrical theory was the Dutch chemist van't Hoff (1852-1911). It was known that there are substances which cannot pass certain membranes permeable to others. If the solution of such a substance (sugar, for example) is contained in a vessel permeable to water though not to the substance dissolved, the water will enter until the difference in level of the liquid inside and outside the vessel represents a definite hydrostatic pressure. This pressure is called the *Osmotic pressure* of the solution. The great contribution of van't Hoff to physical and chemical theory was his discovery that the laws which apply to gases apply also to dilute solutions. He showed that there is a relationship between the osmotic pressure of a solution and the lowering of the freezing-point and raising of the boiling-point noticed in the case of a solution. From the analogy between a gas and a dilute solution, van't Hoff was also able to calculate from theoretical considerations the lowering of the freezing-point and raising of the boiling-point for gramme molecules of soluble substances. With substances like sugar he found his theoretical results to agree with those obtained from experiment, but in the case of solutions of salts and other electrolytes he found the observed results to be far greater than (nearly double) the results demanded by theory.

The facts of electrolysis and of solution were linked up with other physical and chemical phenomena into a consistent theory by a Swedish physicist, Svante Arrhenius. He supposed that in dilute solutions of electrolytes, the molecules are already dissociated into ions, and that these ions travel about freely in the liquid. In his view the mere act of solution results in the dissociation of the molecules. Thus when a solution is introduced into an electrical circuit, the potential difference simply directs the path of the molecules into two main streams. Arrhenius adopted this view after considering the investigations of van't Hoff.

Arrhenius realized the apparently abnormal values observed in the experiments of van't Hoff on this dissociation hypothesis. The dissociated ions he considered as chemically active, and hence capable of exerting osmotic pressure. He denoted the molecules completely dissociated into ions as *active*, and those not so dissociated as *inactive*.[1] He considered that when the solution is very dilute all the inactive molecules are transformed into active ones. At this stage, it is evident that the number of ions would be double the original number of undissociated molecules. This gives a reasonable explanation of the very high values for the depression of the freezing-point and raising of the boiling-point noticed by van't Hoff. A great deal of evidence in favour of the views of Arrhenius can be furnished from further chemical considerations.

§ 5. *Theory of the Voltaic Cell*

For many years the upholders of the rival chemical and contact theories of the voltaic cell entrenched themselves behind their favourite arguments, but no further progress was made until the problem was attacked from other points of view. The new weapon was the doctrine of energy. The transformation of energy from one form to another was realized in a general way long before the middle of the nineteenth century. But it was not until the researches of Joule during the period 1838-1848, and the subsequent work of Kelvin and of Helmholtz, that the principle of the conservation of energy became generally recognized. Joule himself applied the energy principle to the investigation of the heat produced in a voltaic cell.[2] He measured the heat produced and the weight of zinc dissolved as the cell gave current, and concluded that the electromotive force of the cell is proportioned to the mass of zinc dissolved in generating the current.

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[1] *Zeitschrift für Phys. Chem.* i, 1887, p. 631. An extract from the English translation is given in Whetham's *Cambridge Readings in the Literature of Science*, Cambridge, 1924.

[2] 'On the heat evolved by metallic conductors of electricity and in the cells of a battery during electrolysis,' *Phil. Mag.* xix, 1841, p. 260.

It will be remembered that the first chemical cell consisted of two different metals with some kind of liquid conductor between them. It was afterwards found, however, that a current could be obtained from a cell consisting of two similar metals immersed in different electrolytes separated by means of a porous pot. Later it was shown that the electrolytes could be solutions of the same substance, provided the concentrations were different. The last type is known as a concentration cell. Helmholtz was the first to construct such cells, and he pointed out that the energy of the cell is due to the diffusion occurring between the two solutions.[1] Now a substance in solution exerts an osmotic pressure which was shown by van't Hoff to be analogous to gaseous pressure. These considerations were used by Helmholt and applied further by Nernst to the theory of the voltaic cell.

Nernst accounted for the electromotive force of a cell in terms of the work done by the ions in passing from places of high to places of lower concentration, the charge being due to the osmotic pressure exerted by the solutions. When in contact with an electrolyte, Nernst supposed a metal to possess a definite *solution pressure.* By reason of this pressure he considered that the metallic ions enter into solution. This solution pressure may be considered as analogous to the vapour pressure of a liquid. According to Nernst's theory, the metal passes into the electrolyte in the form of charged ions. Thus both the liquid and metal acquire opposite charges. Since opposite charges attract one another, the process of solution will be opposed by the electrical attraction between the ions and the metal, so that ultimately a state of equilibrium is set up.

The solution pressure sets up between the metal and the electrolyte the potential difference called *contact potential.* Now if the two metal electrodes are connected by means of an outside conductor, a current flows, and deposition of metal takes place on one of the electrodes. This means that some of the ions pass out of solution and hence are no longer active, that is they exert no osmotic pressure. More ions can therefore pass into solution. Thus the potential difference between the electrode and electrolyte is maintained and the action of the cell continues. According to Nernst, the original electromotive force of the cell is due to the contact potentials of metal and electrolyte. It is the deposition of the metal, *i.e.* the chemical change when the circuit is completed, that enables the electromotive force of the cell to be continuously renewed. The theory thus included both the contact and chemical theories of the voltaic pile, and so put an end to a long controversy.

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[1] *Wied. Ann.* iii, 1878, p. 201.

[2] *Zeits. Phys. Chem.* ii, 1888, p. 613 ; iv, 1889, p. 129.

IX

THE CONDUCTION OF ELECTRICITY THROUGH GASES

§ 1. *Closing Years of the Nineteenth Century*

Towards the close of the nineteenth century the view was often expressed in more or less naïve language that the great battle of scientific achievement was all but won. The great conquerors of the past, it was believed, had gained the decisive victories at points of vantage; it remained for those left in command to consolidate the positions already won. Certainly the all-embracing doctrine of energy, the remarkable achievement of the master minds of the century, and the enormous development of the practical applications, lent some support to this view. The content of the various branches of science had grown to such formidable dimensions, that university students were often warned against attending to such attractive novelties as the phenomena of the discharge tube, and advised to keep their feet on the solid ground that had been gained. But men of science were not allowed to slumber long. In 1895, Röntgen discovered X-rays; a year later Henri Becquerel observed a new type of radiation from uranium salts; in 1898 the same kind of activity was recognized in the compounds of thorium by M. and Madame Curie. Such phenomena were startling enough to awaken the soundest sleeper, and from that time a new era in the history of physics began.

§ 2. *Early Experiments on the Discharge through Gases*

The new developments may be traced to knowledge of the conduction of electricity through gases. The systematic study of the subject did not begin until the last decades of the century, though even earlier there had been a number of isolated observations of considerable interest. Early in the eighteenth century Hauksbee observed that light is emitted[1] when amber is rubbed on woollen material in a vessel exhausted by means of an air pump. This light, he tells us, could be seen three or four feet away when the vessel was well exhausted, but in ordinary air practically no effect could be seen. The rubbing of the materials *in vacuo* was carried out by means of a spindle passing through the top of the vessel and driven by a hand-wheel from outside.

Some observations on the continuous discharge of electricity through a rarefied gas were made by William Watson, whose experiments on electrostatics we mentioned in Chapter II. A glass tube about three feet long and about three inches in diameter was fitted at the ends with brass caps. Through one of these passed a thin brass rod, the position of which could be varied at will (Fig. 61). Watson first observed the effect of connecting the cap *A*. and rod *B*. to an electrical machine when the air inside the tube was at the ordinary atmospheric pressure. He found that when the distance *A.B.* was two inches a torrent of sparks passed when the electrical machine was worked. When the distance *A.B.* was increased to about five or six inches by moving the brass rod, no sparks could be seen. He then exhausted the tube by means of an air pump, and again passed the discharge through. This time he found that the distance *A.B.* could be increased considerably more, and that in a darkened room the discharge could be seen to pass the whole length of the tube.[2]

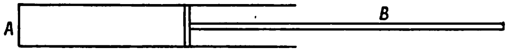

FIG. 61.—TUBE USED IN WATSON'S EXPERIMENTS

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[1] 'Several Experiments on the Attrition of Bodies in Vacuo,' *Phil. Trans.* xxiv, 1705, pp. 2165-2175.

[2] 'An Account of the Phenomena of Electricity in Vacuo with some Observations thereupon, by William Watson, F.R.S.,' *Phil. Trans.* xlvii, 1752, p. 362.

Watson was delighted with the effects he had noticed, and compared the beautiful glow to the 'aurora borealis.' He explained the effect by saying that the electricity is able to push itself through the vacuum by its own elasticity. The pump used by Watson was of the simple type designed by Robert Boyle, and it did not give a very low pressure. Indeed, little progress in the study of conduction through gases was possible until better air pumps were invented. Progress in science often has to wait for improvements in instrumental construction. However, Watson's experiments in the mid-eighteenth century showed conclusively that rarefied air conducts better than air at ordinary pressures, and thus a very important fact was established.

The electric arc is of the nature of a discharge through the air at ordinary pressure. The arc was investigated by Davy in 1821.[1] At the Royal Institution he had at his disposal a voltaic battery consisting of two thousand double plates of zinc and copper. With the aid of this imposing apparatus he obtained an arc or 'column of electric light' when the extreme plates were connected to carbon rods, which were first made to touch and then drawn apart. At this time, it will be remembered, the subject of electro-magnetism was still in its infancy, and Davy was trying to find relations between the phenomena of electricity and magnetism. Having obtained the arc, he brought a powerful magnet near. He found to his surprise that for some positions of the magnet the arc was attracted and in other positions repelled. It is unfortunate that Davy did not investigate the deflection of the arc more completely, for its existence was evidence of a connection between electricity and magnetism. Since this was all that he was looking for, he went no further.

Some years later Faraday experimented on the discharge of electricity through rarefied air with characteristic care and attention to detail.

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[1] 'Further Researches on the Magnetic Phenomena produced by Electricity,' *Phil. Trans.* 1821, p. 425.

> ‘It would seem strange,’ he says, ‘if a theory which refers all the phenomena of insulation and conduction, *i.e.* all electrical phenomena to the action of contiguous particles, were to omit to notice the assumed possible case of a *vacuum*.’ [1]

He describes experiments [2] in which the discharge was passed through air at different pressures and also through vessels containing hydrochloric acid gas, coal gas, hydrogen and nitrogen respectively. The reduced pressures he mentions are 6.5 inches of mercury for some cases and 4.4 inches for others. These were apparently the lowest he could obtain with his air pump. When passing the discharge through rarefied air he noticed that the purple light given off from the positive pole did not reach the negative pole, there being a narrow dark space between the termination of the purple light and the glow surrounding the negative pole. This space has been called *the Faraday dark space*. It is noteworthy that Faraday himself regarded the phenomena of the discharge tube as an important field for research. His words are of great interest in the light of the subsequent development of the subject.

> ‘The results,’ he says, ‘connected with the different conditions of positive and negative discharge will have a far greater influence on the philosophy of electrical science than we at present imagine, especially if, as I believe, they depend on the peculiarity and degree of polarized condition which the molecules of the dielectrics concerned acquire.’

Once again history has shown the words of Faraday to be prophetic.

§ 3. *Progress with Improved Apparatus*

After the invention of the induction coil it became possible to apply far larger potential differences at the terminals of the discharge tube. At the same time the mercurial air pump of Geissler (1814-1879) enabled a greatly diminished pressure to be obtained. Such improved vacuum tubes, usually known as Geissler tubes, were used in the investigations of Plücker of

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[1] *Phil. Trans.* 1838, p. 154.

[2] *Exp. Researches*, §§ 1526, 1552.

Bonn (1801-1868).[1] Plücker observed stratifications visible in the discharge, and found that they could be modified by a magnet outside the tube. The diffused light seen near the negative electrode was found, moreover, to be concentrated by the action of a magnet. He concluded that the glow in the tube consisted of 'lines and light which, proceeding from the separate points of the positive electrode, coincide with magnetic curves.' Plücker emphasized this coincidence with the magnetic curves, and considered this to be the case whatever gas was present in the Geissler tubes.

Some years later, Hittorf, who was one of Plücker's pupils, came to the conclusion that the glow was due to rays of some kind given off in straight lines from the negative pole or cathode. He observed that a small obstacle placed between the negative pole and the wall of the vessel cast a shadow. This casting of a shadow had already been observed in 1876[2] by Goldstein, who found that these *cathode rays*, as they are called, were given off in a direction normal to the surface of the cathode. The new rays attracted much attention. Some thought them to be due to minute particles torn off from the cathode; others regarded them as a kind of ethereal vibration hitherto unrecognized.

The various phenomena connected with the discharge of electricity through gases were examined systematically by Sir William Crookes (1832-1919). In his Bakerian Lecture for 1878,[3] he described in detail the different appearances of the discharge tube at pressures varying from 68 mm. to 0.078 mm. As the degree of exhaustion became greater, he observed that a dark space formed round the cathode and became wider with increasing exhaustion. This particular region in the discharge tube we now know as the *Crookes dark space* (Fig. 62). He considered that electrification of a body by friction produces a molecular vibration which affects the surrounding gas to a slight extent. This molecular disturbance, he considered, extends further the greater the rarefaction of the gas, since it meets with progressively less resistance. The cathode rays he looked on as streams of molecules moving in definite directions. He was perhaps led to adopt this view from the current explanation of the movements of the vanes of his recently-invented radiometer. The width of the dark space he showed to depend on the degree of exhaustion, on the kind of gas in the tube, on the temperature of the negative pole, and on the intensity of the spark. Crookes regarded the substance in an exhausted state as an ultra-gaseous or *fourth state* of matter. He pointed out that, according to the kinetic theory of gases, the number of molecules in a given space is so great that the mean free path is very small, so that the encounters between the rapidly-moving molecules at ordinary pressures are very frequent. But in an exhausted vessel, the free path of the molecules is longer, so that they proceed independently on their way and the hits become less frequent. He considered that the phenomena in exhausted tubes reveal a new world,

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[1] 'On the Action of the Magnet upon the Electrical Discharge in Rarefied Gases,' *Phil. Mag.* xvi, 1858, pp. 119, 408.

[2] *Berlin Monatsberichte*, 1876, p. 279.

[3] 'On the Illumination of Lines of Molecular Pressure and the Trajectory of Molecules,' *Phil. Trans.* clxx, 1879, p. 135; also *Phil. Mag.* vii, 1879, p. 57.

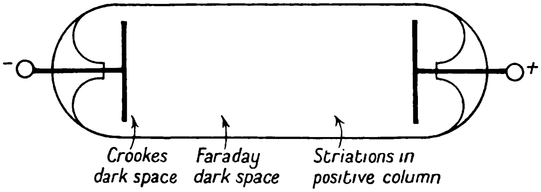

FIG. 62.—DISCHARGE TUBE
showing the positions of the dark spaces and striations

> ‘ a world where matter may exist in a fourth state, where the corpuscular theory of light may be true, and where light does not always move in straight lines, but where we can never enter, and with which we must be content to observe and experiment from the outside.’

Although Crookes had made a number of accurate observations of the phenomena in a discharge tube under different conditions, yet for some years vacuum tubes were regarded as but pleasing scientific toys. The phenomena seemed to defy explanation, and it was some time before any real progress was made. Again and again in the history of physics we find that when experimenters, proceeding according to Baconian principles, collect facts and facts alone, the results are of little value. Progress is more often attained by experiments carried out with the purpose of vindicating or disproving some hypothesis or of establishing some definite numerical result, though the original hypothesis may have to be abandoned or the numerical result subsequently modified. Although there are instances of purely accidental discoveries, yet the man of science when he begins his work, usually has some definite purpose to guide him in his search.

§ 4. *First Evidence as to the Atomic Nature of Electricity*

We have already referred to Faraday's inference as to the possible atomic nature of electricity. In Clerk Maxwell's great *Treatise on Electricity and Magnetism*, published in 1873, there occurs a very significant passage:

> 'Of all electrical phenomena, electrolysis appears the most likely to furnish us with a real insight into the true nature of the electrical current, because we find currents of ordinary matter and currents of electricity forming part of the same phenomenon . . . but if we go on and assume that the molecules of the ions within the electrolyte are actually charged with certain definite quantities of electricity, positive and negative, so that the electrolytic current is simply a current of convection, we find this tempting hypothesis leads us into very difficult ground. . . . Suppose, however, we leap over this difficulty by simply asserting the fact of the constant value of molecular charge, and that we call this constant molecular charge, for convenience in description, *one molecule of electricity*. This phrase, gross as it is, and out of harmony with the rest of this treatise, will enable us at least to state clearly what is known about electricity, and to appreciate the outstanding difficulties.'

Thus Maxwell hesitated in applying the term 'molecule' to electricity, just as Faraday had felt afraid of the term 'atom,' but the atom or molecule of electricity has now been accepted by physicists.

A year after the publication of Maxwell's treatise, G. Johnstone Stoney asserted his belief in the atomic nature of electricity. He went further, for he even estimated the value of the elementary charge in absolute electrostatic units. His views were enunciated at a scientific meeting in 1874, but were not adequately published until 1881.

> 'Nature,' he says, 'presents us in the phenomenon of electrolysis, with a single definite quantity of electricity which is independent of the particular bodies acted upon. . . . For each chemical bond which is ruptured within an electrolyte, a certain quantity of electricity traverses the electrolyte, which is the same in all cases . . . if we make this our unit of electricity we shall probably have made a very important step in our study of the molecular phenomena.' [1]

Stoney estimated the value of the elementary charge from the known quantity of electricity required to liberate one gram of hydrogen in electrolysis and from the number of atoms of hydrogen in the gram-molecule derived from the *Kinetic Theory*. The value so obtained was 0.3×10^{-10} absolute electrostatic units.[2]

During the same year 1881, in his Faraday Lecture at the Royal Institution,[3] Helmholtz expressed his views as follows:

> 'Now the most startling result of Faraday's Law is perhaps this: if we accept the hypothesis that the elementary substances are composed of atoms, we cannot avoid concluding that electricity also, positive as well as negative, is divided into definite elementary portions which behave like atoms of electricity. . . . Electrolytic conduction is not at all limited to solutions of acids or salts. It will, however, be rather a difficult problem to find out how far the electrolytic conduction is extended, and I am not yet prepared to give a positive answer.'

It seems that Helmholtz could not bring himself to consider *metallic conduction* as a transport of elementary portions of electricity. Indeed, the mechanism of metallic conduction was usually pictured as a movement of tubes of force, the energy being dissipated in the form of heat in the conductor. With regard to gaseous conduction, ideas were very confused, and some important pioneer work in the elucidation of the phenomena of the discharge tube was done by Schuster of Manchester during the period 1884-1890.[1]

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[1] 'On the Physical Units of Nature,' *Phil. Mag.* xi, 1881, p. 384.

[2] *Phil. Mag.* xxxviii, 1894, p. 418.

[3] *Proc. Chem. Society*, 1881.

§ 5. *Ionisation of Gases*

Schuster began by considering the elementary charge associated with the ions in electrolysis, and tried to explain conduction in gases from an analogy with liquid conduction. The view that conduction in gases is due to a movement of gaseous ions was proposed by Giese of Berlin in 1882.[2] The same idea was put forward independently by Schuster two years later. There were difficulties in applying the dissociation hypothesis to rarefied gases. One lay in the fact that whereas for acids and salts it is reasonable on chemical considerations to endow the dissociated parts with opposite electrical charges, yet for the pair of atoms derived from, let us say, a hydrogen molecule there seems no justification for assuming such opposite charges. In liquid electrolytes in which no polarization occurs the smallest applied difference of potential suffices to drive a current through the liquid. In a rarefied gas, however, a certain definite electromotive force is required. Now Schuster was able to show in 1887 [3] that a small applied potential difference will give a current through a rarefied gas, provided an independent larger potential difference is applied.

This result obtained by Schuster, which had also been reached by Hittorf, pointed to the conclusion that the larger potential difference caused ionization of the gas. It suggested, too, that the ions so formed could convey the current set up by the smaller applied electromotive force. We have already referred to the deflection of the cathode rays by an outside magnet. This deflection was investigated by Schuster, and used by him in determining the ratio of the charge to the mass of the particle travelling in the cathode stream.

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[1] *Proc. Royal Society*, xxxvii, 1884, p. 317; also Bakerian Lecture for 1890.

[2] *Ann. d. Phys.* xvii, 1882, pp. 1, 236, 519.

[3] *Proc. Royal Society*, xlii, 1887, p. 371.

Assuming the charged particle to be deflected by the magnetic field into a circular path, we can deduce a simple formula for the ratio of the charge to the mass of the particle.

Let m = mass of the particle.
e = charge on particle.
V = fall of potential along the discharge tube.
r = radius of curvature of the circular path described.
H = intensity of magnetic field.
v = velocity acquired by the charged particle.

Then kinetic energy of particle $= \frac{1}{2}mv^2$, and this we can equate to the work done, Ve, during the discharge.

$$\therefore\ Ve = \tfrac{1}{2}mv^2, \text{ giving } \frac{e}{m} = \frac{v^2}{2V} \quad \dots\dots (1)$$

Since the particle is assumed to take a circular path, it follows that the force acting towards the centre must be $\frac{mv^2}{r}$; but if the intensity of the magnetic field is H, that force must also $= Hev$.

$$\therefore\ \frac{mv^2}{r} = Hev,$$

giving

$$v = \frac{rHe}{m};$$

substituting in (1), we obtain $\frac{e}{m} = \frac{2V}{H^2r^2}$.

Since all the quantities on the right-hand side can be measured, the ratio $\frac{e}{m}$ can be determined.

Working at pressures of .3 mm. of mercury, Schuster obtained values of $\frac{e}{m}$ of the order 1.1×10^6. The importance of these early determinations was acknowledged some years later by Sir J. J. Thomson, then Cavendish Professor, now Master of Trinity College, Cambridge.

§ 6. *Commencement of the Modern Period of Physical Research*

The problem of conduction in gases was by now regarded as worthy of the most serious investigation. Even Lord Kelvin, austere and conservative in speculative matters, remarked in 1893:

> 'If the first step towards understanding the relations between ether and ponderable matter is to be made, it seems to me that the most hopeful foundation for it is knowledge derived from experiments on electricity in high vacuum.'

Lord Kelvin's benediction seems, indeed, to have produced an effect, for within the next few years remarkable advances were achieved. Sir J. J. Thomson in 1894 began a series of brilliant investigations on cathode rays, in the prosecution of which the whole subject became raised to the plane of exact measurement.[1] At that time the followers of Crookes believed the rays to be electrified molecules, others of the German School regarded them as ethereal vibrations, relying on the results of Lenard and Hertz.

These experimenters had observed phosphorescence[2] on the walls of a discharge tube with thin films of metal interposed in the path of the cathode rays. Thomson considered that the bombardment of one side of the metal film might send out particles from the other side which would excite phosphorescence on the tube though the original rays had not actually passed through the film. He decided to determine the velocity of the cathode rays, for he considered that if the result differed considerably from the velocity of light, this would be direct evidence against the hypothesis that these rays are a kind of light. Accordingly he devised a means for the determination of the velocity.

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[1] *Phil. Mag.* xxxviii, 1894, p. 358.

[2] The term *phosphorescence* is used to cover a large number of phenomena in which light is emitted, such an emission not being due to combustion in the ordinary sense. The term *fluorescence* is usually applied to those cases in which the emission of light ceases directly the exciting cause is removed.

For the purpose of this experiment Thomson found an induction coil unsuitable owing to the extreme rapidity of the oscillations produced. He therefore used a Leyden jar connected to a transformer to obtain oscillations of suitable frequency. The discharge tube was covered with lamp black, except for two strips in the same line a measured distance apart. The patches of the glass thus visible were seen to be phosphorescent when the discharge was passed through, but the unaided eye was not able to detect any difference in the brightness of the phosphorescence of the two patches. The images were observed in an apparatus consisting of six mirrors arranged symmetrically round a vertical axis and rotating at a measured speed. The experiment was thus similar to the observation of a sensitive flame in a revolving mirror often used in the study of sound. Now if the cathode rays take a finite time to pass from one strip to the next, we should expect to see, in the revolving mirror, not a straight band of light, but some displacement between the drawn-out images. In Thomson's experiment the images were observed through a telescope, and a distinct displacement noticed between the brightest spots of the two phosphorescent patches. The method of calculation will be clearer if we give the actual data obtained.

Speed of rotation of mirror = 300 revolutions per second.
Distance of mirror from discharge tube = 75 cms.
Linear displacement of the images = 1.5 mm.
Distance between the patches = 10 cms.

Then in the time that the mirror turns through an angle of $\frac{1{\cdot}5}{2 \times 750}$ in circular measure, the ray travels a distance of 10 cm.

But the mirror turns through an angle 2π in $\frac{1}{300}$th of a second, which gives the velocity of the cathode rays as

$$\frac{1{\cdot}5}{2 \times 750 \times 2\pi \times 300} \text{ cm./sec.}$$

$$= 1.9 \times 10^7 \text{ cm./sec.}$$

This being far less than that of light (viz. 3×10^{10} cm./sec.) was evidence in favour of the charged particle hypothesis.

Further evidence was obtained by the French physicist Jean Perrin, who found, in 1895,[1] that when cathode rays are caught in a metal cylinder, the latter becomes negatively charged. Perrin concluded, therefore, that cathode rays are negatively charged particles of some kind, although his result did not carry conviction with the supporters of the ether wave hypothesis.

During the autumn of 1895, Wilhelm Conrad Röntgen (1845-1923), Professor of Physics, then of Würzburg, was experimenting with discharge tubes. Some photographic plates had been kept in the room where the experiments had been conducted. These, when used, were found to be badly fogged. The plates had been protected from light in the usual manner. Röntgen perceived that something unusual had occurred. Within a week he had traced the accident to its true source, and had succeeded in establishing many properties of this new kind of radiation. For the sake of brevity he gave the name of *X-rays* to this new effect. The term *ray* he considered was justified, since the effect, whatever its nature, seemed to proceed in straight lines and to cast shadows, in these respects resembling ordinary light.[2] Röntgen found that the new rays are more penetrating than ordinary light, so that if a hand is held in their path, and a screen of fluorescent substance provided, the rays penetrate the flesh and cast a shadow of the bones.

Röntgen showed that X-rays are generated when cathode rays strike the glass walls of the discharge tube (Fig. 63). The cathode stream can be deflected to another point by means of a magnet, and if this is done the X-rays proceed from this new point. Röntgen did not succeed in refracting X-rays by any new substance which can refract ordinary light, and he found that X-rays could not themselves be deflected by a magnetic field. He concluded that the X-rays are therefore quite different from cathode rays, and different also from light.[1] Their discoverer suggested that these rays are due to a longitudinal disturbance of the ether, ordinary light being a transverse vibration.[2]

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[1] *Comptes Rendus*, cxxi, 1895, p. 1130.

[2] Über Eine Neue Art von Strahlen. A translation of the original paper, read before the Physico-Medical Society of Würzburg, appeared in *Nature*, liii, 1896, p. 274.

Röntgen's discovery soon excited the interest of the world at large. The obvious application to the needs of surgery was at once realized. The laboratories of the physicists of the time were besieged by medical men in order that the new rays might be used to locate pins, needles or bullets somewhere hidden inside a suffering patient! At the present time X-rays are used in the diagnosis of certain diseases, as well as for the detection of fractures and foreign bodies, but such applications do not concern us here.

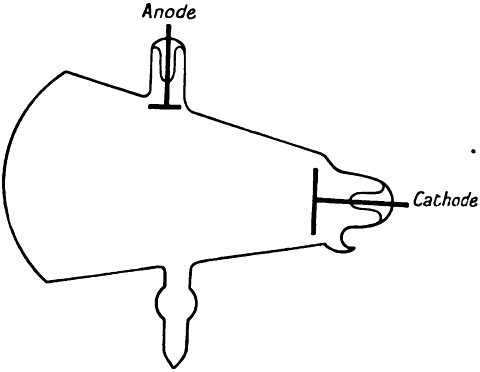

FIG. 63.—TYPE OF TUBE WITH WHICH RÖNTGEN DISCOVERED X-RAYS

From the point of view of the development of our knowledge of electricity, the most important property of X-rays is their power of rendering a gas a conductor, that is to say, of *ionising* it. This power of X-rays was announced by J. J. Thomson [3] shortly after Röntgen's results became known, and subsequently investigated in collaboration with E. Rutherford.[1] Thomson and Rutherford found that a gas rendered conductive by exposure to X-rays, lost that property if forced through a plug of glass wool. The carriers of the current, whatever their nature, were therefore large enough to be ' filtered ' off. They also found that for a constant X-ray intensity of radiation, the current that could be passed through the gas increased with the electromotive force applied, but approached a limiting value. This fact pointed to the conclusion that a definite ionisation was produced by the X-rays in the first instance, and that the applied electromotive force merely directed the path of the ions as in electrolysis.

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[1] X-rays have since been identified as light of very short wave-length. See W. H. Bragg and W. L. Bragg, *X-Rays and Crystal Structure*, 4th edition, London, 1924.

[2] Those interested in ether theories will remember that the longitudinal disturbance had so far eluded discovery.

[3] *Nature*, 27th Feb., 1896, p. 391.

The following year (1897) J. J. Thomson published results of great importance dealing with the nature of cathode rays.[2] It will be remembered that Schuster had made measurements of the deflection of cathode rays by a magnetic field (see p. 161), and had obtained a value for the ratio *e/m* ; J. J. Thomson, with improved apparatus, succeeded in deflecting the rays by means of an electrostatic field, and calculated the ratio *e/m* as well as the velocity. Perrin had found that cathode rays carry a negative charge, but J. J. Thomson provided more conclusive

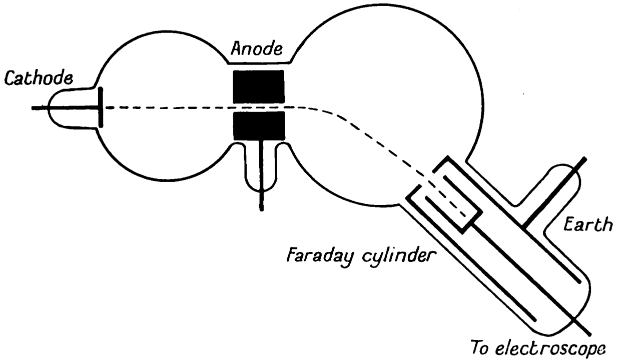

FIG. 64.—J. J. THOMSON'S MODIFICATION OF PERRIN'S TUBE

evidence, for by means of a specially constructed discharge tube (Fig. 64) he showed that the cathode rays, however contorted in their path by a magnetic field, convey the negative charge in the same direction. He concluded, therefore, that the negative charge is indissolubly connected with the cathode rays. The experiments on which he based his determination of the velocity and the ratio of the charge to the mass of the cathode particle, are of the most far-reaching importance.

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[1] ' On the Passage of Electricity through Gases exposed to X-Rays,' *Phil. Mag.* xlii, 1896, p. 392.

[2] *Phil. Mag.* xliv, 1897, p. 293.

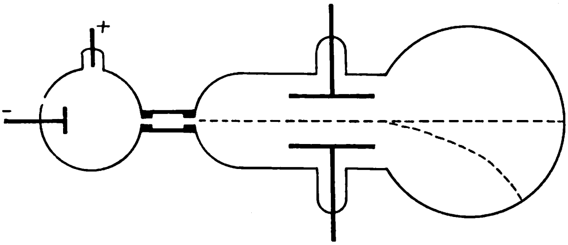

Fig. 65.—Discharge Tube used in J. J. Thomson's experiments.

In these experiments J. J. Thomson used a large discharge tube in which an electric field was maintained between two aluminium plates, so placed that the direction of the field was at right angles to the course of the rays. In order to maintain a stream of rays along the axis of the tube, the rays passed through slits in two earth-connected plugs, one of which formed the anode as shown (Fig. 65). The rays on striking the far end of the tube rendered the glass fluorescent. When the aluminium plates were connected to a battery of accumulators an electrostatic field was set up, and the deflection of the fluorescent patch in the bulb could be clearly seen. The experiment consisted in deflecting the cathode rays first by an electrostatic field and then by a magnetic field, and adjusting the strength of these fields so that the two deflections were equal.

Let m = mass of cathode particle.
e = charge carried.
v = velocity.
F = intensity of electrical field.
H = intensity of magnetic field.

Then suppose l is the length traversed under the electrical field, the time taken is l/v, and the velocity generated in the direction of F is clearly

$$\frac{Fe}{m}\frac{l}{v}$$

Hence, if θ be the angle of deflection when the rays enter the free region beyond the plates, we have

$$\theta = \frac{\text{velocity generated}}{\text{original velocity}}$$

$$= \frac{Fe}{m} \cdot \frac{l}{v^2}.$$

Similarly, the velocity generated by the magnetic force

$$= \frac{Hev}{m}\frac{l}{v}$$

and the angle of deflection $\phi = \dfrac{Hev}{m}\dfrac{l}{v^2}$

$$= \frac{Hel}{mv}$$

Hence, $$\frac{m}{e} = \frac{H^2\theta l}{F\phi^2}$$

and $$v = \frac{\phi}{\theta}\frac{F}{H}$$

But, since the fields were adjusted so that $\theta = \phi$, we have

$$v = \frac{F}{H}$$

and $$\frac{m}{e} = \frac{H^2 l}{F\phi}, \text{ or } \frac{e}{m} = \frac{F\phi}{H^2 l}.$$

Sir J. J. Thomson applied this method to a determination of velocity of cathode rays and the ratio of charge to mass in a large number of cases; sometimes with traces of air in the discharge tube, and at other times with traces of other gases. He found remarkably constant results, the value for the velocity of the cathode rays being of the order $2{\cdot}8 \times 10^9$,[1] and the ratio of charge to mass 10^7. The value of this ratio may be attributed either to the smallness of the mass or to the magnitude of the charge, or to both. Now the value of the ratio $\frac{\text{charge}}{\text{mass}}$ for the hydrogen ion in electrolysis had been found to be of the order 10^4. Whence it follows that if the charge carried by the cathode particle were the same as that carried by the hydrogen ion, the mass of the cathode particle must be considerably less than that of the hydrogen ion. Therefore the cathode particles would have to be regarded as but small fragments of atoms.

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[1] This result is considerably higher than that given by the earlier experiments of 1894.

Conclusive evidence for the fragmentation of the atom was furnished later. Even at the time of these experiments (1897), however, Sir J. J. Thomson showed that certain results pointed to the conclusion that the cathode particles were smaller than ordinary atoms. These results were based on the observations of Lenard on the passage of cathode rays through air. Lenard showed that a cathode ray has to travel through air a distance of half a centimetre before losing a large part of its power to produce phosphorescence by loss of momentum. An ordinary gaseous molecule, however, travelling in air at the same pressure would lose as much as half of its momentum after travelling a distance comparable with its mean free path, which for the pressures considered is but $\frac{1}{100000}$ of a centimetre. This provides evidence of the extreme minuteness of the mass of these cathode particles.

From these facts Sir J. J. Thomson felt there was justification for supposing the cathode ray particle to be very small. He suggested that in the cathode rays we might be dealing with the primordial substance from which all atoms are built up, an hypothesis suggested many years before by Prout (1785-1850), who thought that all the chemical elements were built up from hydrogen. 'On this view,' said Sir J. J. Thomson in 1897,

> 'we have in the cathode rays matter in a new state, a state in which the sub-divisions of matter is carried very much further than in the ordinary gaseous state: a state in which all matter, that is matter derived from different sources such as hydrogen, oxygen, etc., is of one and the same kind; this matter being the substance from which all chemical elements are built up.'[1]

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[1] *Phil. Mag.* xliv, 1897, p. 312.

The following year, he succeeded in measuring directly the charge carried by the cathode particle. His results showed that the charge is the same as that carried by the hydrogen ion in electrolysis. An entirely new method of experiment was employed, based on a discovery of C. T. R. Wilson of Cambridge, that in a gas that has been exposed to Röntgen rays, the negative ions act as nuclei for the formation of drops of water. J. J. Thomson exposed to ionisation by X-rays dust-free air, supersaturated with water vapour. On suddenly allowing the air to expand, it became cooler and a cloud of small drops were formed. From the rate of fall of the drops, it was possible to calculate their volume from a formula given by Sir George Stokes. The volume of the condensed water was easily determined by simple measurement as soon as the cloud had completely fallen to the bottom of the vessel. Hence, the number of drops and therefore the number of nuclei or ions could be calculated. An independent measurement of the current conveyed by the ions enabled the total charge on all the ions to be calculated. This, divided by the number of ions previously found, gave the individual charge carried.

Sir J. J. Thomson's first experiments gave a value of the order 7×10^{-10}. Subsequent improvements by H. A. Wilson and Sir Ernest Rutherford gave a value $4{\cdot}65 \times 10^{-10}$ electrostatic units. J. J. Thomson's results were made known to the scientific world at a meeting of the British Association at Dover in 1889, and he succeeded in convincing his hearers that cathode rays consist of a stream of particles of considerably less mass than atoms, carrying a constant negative charge. He called the cathode particles 'corpuscles,' but it has now become customary to call them 'electrons,' this word having been originally used in 1891 by Johnstone Stoney to denote the unit of charge carried by the hydrogen ion in electrolysis. The following extract from his address to the British Association summarizes the views of Sir J. J. Thomson at the time.

> 'I regard the atom as containing a large number of smaller bodies which I will call corpuscles; these corpuscles are equal to

each other; the mass of a corpuscle is the mass of the negative ion in a gas at low pressure, *i.e.* about 3×10^{-26} of a gramme. In the normal atom, this assemblage of corpuscles forms a system which is electrically neutral. Though the individual corpuscles behave like negative ions, yet when they are assembled in a neutral atom the negative effect is balanced by something which causes the space through which the corpuscles are spread to act as if it had a charge of positive electricity equal in amount to the sum of the negative charges on the corpuscles. Electrification of a gas I regard as due to the splitting up of some of the atoms of the gas, resulting in the detachment of a corpuscle from some of the atoms. The detached corpuscles behave like negative ions, each carrying a constant negative charge, which we shall call for brevity the unit charge; while the part of the atom left behind behaves like a positive ion with the unit positive charge and a mass large compared with that of the negative ion. On this view, electrification essentially involves the splitting up of the atom, a part of the mass of the atom getting free and becoming detached from the original atom.'

X

ELECTRICAL CONSTITUTION OF MATTER

§ 1. *Radioactivity*

WHILE J. J. Thomson was attacking the problem of cathode rays, remarkable discoveries had been made by other workers. Röntgen's new rays had roused the interest of the scientific world. Henri Becquerel, during the course of investigations in search of the connexion between X-rays and fluorescence, lighted on yet another order of ray. He examined many fluorescent substances. In 1896 he announced to the French Academy the discovery of a new kind of radiation given off from uranium and its compounds. This radiation excited fluorescence, affected a photographic plate, and was able to pass through thick black paper. Becquerel showed that the rays are able to ionise a gas, thus resembling cathode and X-rays.[1] Two years later M. and Mme. Curie found that thorium and its compounds gave off the same kind of radiation,[2] and that this power was possessed in a still more marked degree by the natural mineral pitchblende, which is more active than uranium itself. This fact suggested that pitchblende contains some very active constituents. It was not long before two new elements, *radium* and *polonium*, were isolated from it.

In 1899 Sir Ernest Rutherford began a series of investigations on the radiation from uranium and similar substances.[3] Rutherford showed that at least two distinct types of radiation are given off from uranium. One type, which he called α rays, are able to ionise a gas, but do not possess high powers of penetration. The other type, which he named the β rays, have greater penetrating power. Shortly after the publication of Rutherford's first results, Becquerel and others [1] showed that they are deflected by a magnetic field, and the Curies found that they carry negative charges. Thus it seemed as if the β rays were identical with cathode rays. Measurements of the velocity of the β rays and the ratio $\frac{\text{charge}}{\text{mass}}$ by methods similar to those already described,[2] showed that they consist of cathode ray particles, that is electrons, of extremely high velocity. Further investigation of radioactive substances led to the recognition of a third type of radiation, the γ rays, which were identified with X-rays. Rutherford had found that radioactivity is always accompanied by the formation of new chemical substances, and this led him to propose, in collaboration with Soddy, the disintegration hypothesis.[3] Radioactivity is thus considered to be due to an explosive splitting up of the chemical atom, and since rays are at the same time expelled, they must have been present in the original atom. α rays when allowed to accumulate were always found to give the characteristic spectrum of helium. From deflection experiments like those we have indicated above (p. 168), it was shown that these α rays carry a positive charge and consist of particles of atomic mass. Thus the α rays were identified as positively charged helium atoms, and hence it seemed reasonable to conclude that the atom of a radioactive element contains electrons and charged helium atoms. The atom had long been regarded as the unit of matter, indivisible and unchangeable. But here was an instance of a complex atom breaking up into something simpler. Still more convincing evidence of the complexity of atoms resulted from the achievements of the next few years.

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[1] *Comptes Rendus*, cxxii, 1896, p. 420.

[2] *Ibid.* cxxvii, 1898, p. 175.

[3] *Phil. Mag.*, xlvi. 1899, p. 109.

[1] *Comptes Rendus*, cxxx, 1900, p. 809.

[2] Kaufmann, *Phys. Zeits.* iv. 1b, 1902.

[3] E. Rutherford and F. Soddy, *Phil. Mag.* v, 1903, pp. 95, 117, 445.

§ 2. *Electrons and Protons*

The researches of J. J. Thomson in 1897 had proved the existence of the electron, a sub-atomic particle carrying a constant negative charge. Ingenious methods for the measurement of this unit charge have been devised by Millikan of Chicago.[1] Instead of examining the fall of a cloud of drops, as in the method of C. T. R. Wilson and J. J. Thomson, Millikan experimented on individual droplets of oil balanced between two charged plates. He succeeded in showing that the charge given to such a droplet is always the electronic charge or an integral multiple of that charge. This was additional evidence for regarding the electron as the fundamental unit of negative electricity.

Electrons were first revealed in a very out-of-the-way place, the discharge tube of the physicist. Now they can be detected in many places. Not only are streams of high-speed electrons given off from radioactive substances, but they are evolved under the action of ultra-violet light and during many chemical reactions. Electrons are given off by hot metals, the *thermionic valve* used in ordinary valve-receiving sets for wireless depending on this fact. Since electrons are given off from hot bodies on the earth, it is reasonable to suppose that streams of electrons are sent out by an enormously hot body like the sun. The fast-moving electrons of a discharge tube are deflected by a magnetic field, and they also give rise to luminous effects. Does it not therefore seem probable that the electrons shot off from the sun will excite luminosity in the rarefied air of the upper atmosphere, and be affected in some way by the magnetism of the earth? Perhaps the electron stream from the sun accounts for the aurora borealis and other natural phenomena.

When the nature of cathode rays had been established, physicists began to seek to demonstrate the opposite kind of rays consisting of positively charged particles. In 1886, when the discharge tube was still in its infancy, Goldstein had shown that if the metal cathode of a specially made vacuum tube is drilled with a large number of small holes a luminous discharge streams from the holes into the upper part of the tube. These he called 'Kanalstrahlen,' because of the method by which he had detected them.[1]

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[1] *Phil. Mag.* xix, 1910, p. 209; and Millikan, *The Electron*, Chicago, 1917.

The Kanalstrahlen were investigated later by J. J. Thomson.[2] By means of deflection experiments similar to those he had devised for the examination of cathode rays, he showed them to consist of positively charged particles, the mass of which depended on the nature of the residual gas in the discharge tube. The name *positive rays* suggested by J. J. Thomson is now in general use. The positive rays have rendered possible an entirely new method of chemical analysis. By passing a discharge through an exhausted tube and submitting the positive rays to the combined action of electric and magnetic fields, the deflected beam could be focussed and recorded on a photographic plate. In this way a kind of spectrum was obtained with characteristic lines corresponding to those particles with the same value of m/e. An examination of this so-called mass spectrum led to the discovery of *isotopes*, that is atoms chemically inseparable but of slightly different atomic weight.[3] The proof of the existence of isotopes has brought us back to Prout's hypothesis, and we now believe that all atoms are built up of the same common constituents.

The unit of negative electricity, the electron, which has the value $4{\cdot}774 \times 10^{-10}$ electrostatic units, is always associated with a mass $\frac{1}{1800}$th of that of the hydrogen atom. The corresponding quantity of positive electricity, however, is always found with a mass of atomic order. The unit charge associated with a mass, that of the hydrogen atom, is now regarded as the unit of positive electricity. It is called the *Proton*. Electrons and protons are considered to be the fundamental atoms of electricity from which all substances are made.

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[1] *Berl. Sitz Ber*, 1886, p. 691.

[2] *Phil. Mag.* xiii, p. 561; and J. J. Thomson, *Rays of Positive Electricity*, Cambridge, 1913.

[3] F. W. Aston, *Isotopes*, Cambridge, 1922.

§ 3. *Electricity and Matter*

The vast extent of the subject and the voluminous literature of modern research makes any attempt at an historical treatment of modern work extremely difficult. The isolation of the electron and the investigation of the changes undergone by radioactive substances led to the conception of the atom as an electrical structure. Different atom models have been devised from time to time to fit in with observed phenomena, but both physicists and chemists are agreed to regard the atom as consisting of a nucleus surrounded by electrons. There is experimental evidence to support the view that the nucleus is built up of protons and electrons, and that practically the whole mass is concentrated in the nucleus. The resultant charge on the nucleus is positive, and in a neutral atom this charge must be equal to the number of outside electrons. It was found that the fast-moving α particles shot off from radioactive substances can be made to pass through the atoms of matter, and that in doing so they are sometimes deflected suddenly from their former straight path. From observations of these deflections it was concluded that within the atom there is a strong electric field due to a charged nucleus.

A remarkable relationship was discovered by Moseley,[1] a a brilliant young physicist who was killed at Gallipoli in 1915. If the atoms are arranged in the order of their atomic weights, beginning with hydrogen as 1, the 'place' of an element on the list is called its atomic number. Moseley investigated the X-ray spectra of a great number of elements by using a bulb in which the target consisted of the different materials to be examined. The spectrum of the X-rays given off was observed by the crystal grating method.[2] He found that a similar spectrum was obtained for all elements, and that the frequency corresponding to similarly situated lines in the spectra of different elements was proportional to the square of the atomic number. This led him to conclude that the positive charge of the nucleus is numerically equal to the atomic number. This striking conclusion has been verified by Rutherford and his followers. Moseley's work has opened up a new field of experimental enquiry, as well as being of fundamental importance in the modern theory of atomic structure.

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[1] *Phil. Mag.* xxvi., 1913, p. 1024.

[2] W. H. Bragg and W. L. Bragg, *X-Rays and Crystal Structure*, London, 1924.

The tremendous speed with which electrons, α particles or X-rays are shot off from a disintegrating atom of a radioactive substance show that we have in such substances a very concentrated source of energy. It was by bombarding nitrogen with swift α particles given off from radium that Rutherford succeeded in breaking up the nitrogen atom.[1] He showed conclusively that hydrogen nuclei are the product of such disintegration. There can be no doubt that the nucleus of an atom is held together by very powerful forces, and that the electrons surrounding the nucleus must, under certain conditions, be moving with a very high velocity. Moving electrons are moving 'static' charges, and hence constitute electric currents, which in their turn give rise to magnetic fields. A rapidly alternating electric intensity sets up electro-magnetic waves, and we have seen how light may be interpreted as an electro-magnetic disturbance. A changing magnetic field behaves as if it 'had' inertia, and according to present views the properties usually associated with mass are equally well explained by supposing that matter consists of atoms of purely electrical nature. Thus electricity becomes the fundamental entity; but if we ask: What is electricity? we are left with an unanswered question. Ultimate truth, whatever that may be, is for ever out of reach, and the final explanation of physical phenomena may be a dream which forever eludes our grasp.

The achievements of the last twenty-five years have resulted in the triumph of the atomic theory of electricity and of matter—

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[1] 'Stability of Atoms,' *Proc. Phys. Soc.*, 10th June, 1921.

if we may be pardoned for preserving that distinction. Entirely new experimental methods have been devised and powerful theoretical instruments have been used to attack fresh problems. Now that atoms are no longer little hard pellets but possess a structure, physics has given us further complexities with which to grapple. But an important feature of modern theory is the degree of simplification it has already introduced and the extent to which it has co-ordinated knowledge of different fields. It is not too much to say that the physics of the twentieth century has indeed created a different world for us, and once more all things are made new.

INDEX

α-rays, 173, 177, 178
Active molecules, 150
Adamant, 1
Adamant Stone, 1
Aepinus, Francis Ulrich, 37, 53
Aerial, in wireless circuit, 139
Air pump, mercurial, 156
Albertus Magnus, 2
Alternating currents, 103, 106, 147
Amber, 1, 11
Ampere, unit of current, 72, 80, 121
Ampère, André Marie, 60-73; his researches, 63-73, 97, 110; other references, 54, 75, 85, 90, 92, 100, 123, 124
Ampère, Jean Jacques, 60
Anion, 146, 147, 148
Anode, 141, 145
Arago, D. F., 57, 58, 76, 86; *see also* Rotations
Arc, electric, 155
Armature, of dynamo, 103
Arrhenius, Svante, 51, 149, 150
Ascoli, Cecco d', 5
Astatic balance, Ampère's, 66-8
— galvanometer, 75, 108, 112
Atom, structure of, 170-2, 176-9; of electricity, 149, 150, 160, 177
Atomic number, 177, 178
Attracted disc electrometer, 118
Aurora borealis, 155, 175
β-rays, 174
Bacon, Francis, 89
Bacon, Roger, 2, 4
Balance: Ampère's astatic, 66-8
— Christie's resistance, 109, 110
— torsion, 36, 37, 53
Ballistic galvanometer, 120
Banks, Sir Joseph, 44, 45
Becquerel, Henri, 153, 173, 174
Beddoes, T., 46
Bennet, Abraham, 30
Berzelius, Jons Jacob, 51
Biot, J. B., 58; Law of Biot and Savart, 58, 68, 71
Bismuth, diamagnetic properties of, 101
Black, Joseph, 17
Boiling point, elevation of by substances in solution, 149
Boyle, Hon. Robert, 12, 14, 15, 16, 155
Bragg, Sir William, and W. L., 166, 177
British Association, 121, 128, 171
Brushes, of dynamo, 103
Bunsen cell, 146
Buonaparte, Napoleon, 44, 62
Calcination, 17
Caloric, 16
Caloric theory, 17
Cambridge: Cavendish Laboratory, 128
Cambridge Philosophical Society, 126
Capacity, 33; specific inductive, 33, 123, 134, 135, 143, 144
Carlisle, Anthony, 44, 45
Cathode, 142, 145
Cathode rays, 157, 158, 161-71, 173-6
Cation, 146, 147, 148
Cavendish, Hon. Henry, 31-6, 37, 44, 76, 129, 144
Cell: Bunsen, 146; concentration, 151; Daniell, 120, 146; Grove, 146; Leclanché, 146; Voltaic, 150-2
Centimetre, fundamental unit of length, 114
Christie, S. H., 109
Clausius, R. J. E., 51, 145
Cobalt, magnetic properties of, 100
Colour and colour vision, 126, 130
Commutator, of dynamo, 103
Compass, 2 sqq.; needle, 7
Concentration cell, 151
Condenser, 33, 105, 143
Conduction, electric, 19, 20, 77, 78
Conduction of electricity through gases, 153-72
Conductivity, 75, 76; of electrolytes, 145, 147, 148; of metals, 33, 34; of water, 34
Conductors, 21
Contact potential, 151
Contact theory, 45
'Corpuscles,' 171, 172
Corpuscular theory of light, 16, 158
Coulomb, Charles Augustin, 36-8, 53
Crookes, Sir William, 157, 158, 163
Crystal, in wireless receiver, 139
Crystal grating, for X-ray spectra, 177
Curie, M. and Madame, 153, 173-4
Current, 40-52, 78-80; absolute measurement, 116, 118; alternating, 103, 106, 147; direct, 103; displacement, 133, 134; electro-magnetic unit of, 115,

116; induced, 89, 91 sqq., 132; measurement of, 111; practical unit of, 121; thermo-electric, 75
Dalton, J., 52
Daniell, Frederick, 120, 145-7
Dark space: Crookes, 157, 158; Faraday, 156
Davy, Sir Humphry, 46-50, 62, 82, 141; on conductivity, 76; on the electric arc, 155; and Faraday, 82-6, 88
de la Rive, Auguste, 51, 84, 141
de la Rive, Charles, 84
Declination, 8, 11
Desaguliers, Jean Théophile, 19-21
Desormes, 54
Diamagnetism, 101, 124
Dip, magnetic, 8-12
Direct currents, 103
Discharge through gases, 153 sqq.
Discharge tube, 158, 161-4, 168
Disintegration, of atoms, 178
Disintegration hypothesis, 174
Displacement current, 133, 134
Dissociation, electrolytic, 144-52
Dryden, John, 12
du Fay, Charles-François, 21
Dynamo, 103, 104, 146
Dyne, C.G.S. unit of force, 115
Edinburgh Royal Society, 126
Effluvium, 17
Electric induction, 30
Electric light, 104, 155
Electrical machines, 28, 29, 62
Electrical measurements, 103-21
Electrical theory, development of, 122-40
Electricity: etymology of term, 11; early eighteenth-century conceptions of, 17 sqq.; and heat, 75
Electrics, 11, 21
Electrification, degree of, 33
Electrodes, 141, 146, 147
Electrodynamometer, 111
Electrolysis, 44, 141-52, 159-61, 167, 171; Davy's work on, 48-50; Davy and Grothus's theory of, 50, 141, 144; Faraday's laws, 100, 141-4, 148; Daniell's work on, 145-6; other experimenters, 149-52
Electrolytes, 142, 145-9, 151, 152, 159, 161
Electrolytic dissociation, 144-152
Electro-magnetic induction, 58, 81-102
— rotations, 86, 87, 90; *see also* Rotations
— theory of light, 101, 133-6, 144
— unit of current, 115, 116, 123, 124
— waves, 136-40, 178
Electro-magnetism, 53-80, 85-7, 89
Electrometer, absolute, attracted disc, 118; quadrant, 117, 118
Electromotive force, 79, 80, 132; induced, 97 sqq.; practical unit of, 120, 121
Electron, 123, 171, 174, 175-7
Electroscope, Gilbert's, 12; gold-leaf, 30, 45; pith ball, 34, 35
Electroscopic force, 78, 79
Electrostatic field, 133
Electrostatic units, 115, 123, 124
Electrostatics, 14, 16-39, 132
Electro-tonic state, 97
Energy, conservation of, 150, 153; of electric current, 133
Ether, 71, 135, 136, 163, 165, 166
Ewing, 125
Faraday, Michael, 81-102; and Davy, 82-6, 88; Faraday's laws of electrolysis, 141-4, 148; his work on discharge through gases, 155-6; 'dark space,' 156, 158; other references, 27, 33, 39, 56, 57, 58, 80, 103, 104, 124, 126, 128, 130, 145, 159, 167
Fleming, J. A., 139
Fluorescence, 163
Force, electromotive, 79, 80, 132; electroscopic, 78, 79; lines of, 73, 91, 130
Fourier, J. B. J., 73, 77
Franklin, Benjamin, 23, 24-7, 28, 37, 53, 54, 62
Freezing point, lowering of by substances in solution, 149
Fuller, Mr., 101
Fuller, Thomas, 6
γ-rays, 174
Galileo, 12
Galvani, Luigi, 40-3
Galvanism, 42, 43, 55, 57
Galvanometer, 73-5, 110; astatic, 75, 108, 112; ballistic, 120; moving coil, 112; tangent, 71, 110, 116
— Helmholtz's, 110; Kelvin's mirror, 112; Weber and Kohlrausch's, 124

Gases, conduction of electricity through, 153-72; discharge through, 153-6; ionisation of, 161, 162, 166, 167, 171, 172, 173; kinetic theory of, 130, 160
Gauss, K. F., 111; his method of measuring *H*, 115, 116
Geissler, H., 156
Geissler tubes, 156, 157
Giese, 161
Gilbert, William, 5-13
Glass, diamagnetic properties of, 101
Goldstein, 157, 176
Göttingen, magnetic observatory at, 111
Gramme, fundamental unit of mass, 114
Gray, Stephen, 19, 20, 21
Green, George, 122
Grothuss, Theodor von, 50, 141
Grove cell, 146
Guericke, Otto von, 28
Hachette, 54, 92
Halley, Edmund, 12
Harris, John, 17
Hauksbee, Francis, the elder, 28, 29, 154
Heat, 14, 16, 18, 77; and electricity, 75
Helical currents, 65
Helium, 174
Helmholtz, Hermann von, 110, 137, 150, 151, 160
Henry, Joseph, 100
Hertz, Heinrich, 137-9, 163
Hittorf, 51, 147, 148, 157, 161
Horizontal component of earth's magnetic field, 111, 115, 116
Huygens, Christian, 16
Imponderables, doctrine of, 16, 17
Inactive molecules, 150
Induced currents, 89, 91 sqq., 123, 132
Induction, electric, 30; electro-magnetic, 58, 81-102
Induction coil, 104-6, 137-9, 148, 156
Influence, electrification by, 30
Institution of Civil Engineers, 104
International Congress on Electrical Units, 121
Inverse squares, law of, 27, 28, 32, 34-8, 53, 70
Ionic theory, 51-2, 149-50
Ionisation of gases, *see* Gases
Ions, 142, 145, 147, 148, 159, 161; gaseous, 161, 167, 171, 172
Isotopes, 176
Joule, J. P., 17, 170
Kanalstrahlen, 176
Kelvin, Lord, 31, 111-14, 117, 118, 122, 123, 125, 129, 137, 150, 163
Kinetic theory of gases, 130, 160
Kirchhoff, G. R., 118-19
Kohlrausch, 51, 123, 124, 135, 147, 148
Lagrange, J. L., 38, 89
Laplace, P. S. de, 38, 73
Lavoisier, A. L., 17
Leclanché cell, 146
Lenard, 163, 170
Lenz, Emil, 95
Leyden Jar, 22-4, 33, 42, 44, 124, 137, 164
Light, 16, 18; electric, 104, 155; corpuscular theory, 16, 158; electro-magnetic theory, 101, 133-6, 144; wave theory, 16, 32, 135; ultra-violet, 175; velocity of, 124, 135, 136, 138, 163, 165; and magnetism, 101
Lightning, 27
Lightning conductor, 27
Lines of force, 73, 91, 130
Lines of magnetic force, 96-100
Lodestone, 1, 2, 6-8
Lodge, Sir Oliver, 138, 139
Loud-speaker, wireless, 107
Louis XV, 21
Magnesia, 1
Magnesian stone, 1
Magnet, 1 sqq.; artificial, 53; *see also* Electro-magnet
Magnetite, 1
Magnetic moment, 116, 122
Magnetic pole, unit, 115
Magnetic shell, 71, 72
Magnetic Union, 111
Magnetism, 1 sqq., 52, 53 sqq.; and light, 101; *see also* Electro-magnetism
Magnetization, intensity of, 122
Magneto, of internal combustion engine, 105, 106
Magnetometer, 111; in measurement of *H*, 115, 116
Marconi, G., 139
Maxwell, James Clerk, 125-138; on inverse square law, 36; other references, 31, 57, 70, 118, 124, 143, 144, 159, 160
Measurements, absolute, 114, 115; electrical, 103-21

Metre, 114
Michell, John, 37, 53
Millikan, 175
Molecular theory of magnetism, Weber's, 124, 125
Molecular vortices, Maxwell's hypothesis of, 131, 132
Molecule, of electricity, 159
Molecules, partial, in Clausius's theory, 145
Moment, magnetic, 116, 122
Moseley, 177, 178
Motor, electric, 103, 104
Multiplier, 91
Musschenbroek, Pieter van, 22, 23
Nernst, 51, 151, 152
Newton, Sir Isaac, 12, 16, 32, 38, 73, 89
Nicholson, William, 44, 45
Nickel, magnetic properties of, 100
Nobili, 74, 108
Nollet, Abbé Jean Antoine, 22, 23
Non-conductors, 21
Non-electrics, 11, 21
Norman, Robert, 9, 10
North pole, *see* Poles
Null method, 66, 110
Oersted, Hans Christian, 54-57 ; 52, 63, 66, 73, 75, 76, 85, 86, 90, 100
Ohm, practical unit of resistance, 80, 121
Ohm, Georg Simon, 76-80, 108
Ohm's law, 78, 79, 80, 108, 109 ; for solutions, 145, 147, 148 ; theory of the Galvanic Circuit, 79
Ohmad, practical unit of resistance, 121
One Fluid Theory, 26, 37, 53
Optics, 126
Oscillations, electric, 137
Osmotic pressure, 149, 151, 152
Peregrinus, Petrus, 2-4
Permeability, 123, 135
Perrin, Jean, 165, 167
Phlogiston, 17
Phosphorescence, in discharge tube, 163, 164, 170
Pitchblende, 173
Pliny, 2
Plücker, 156, 157
Poisson, S. D., 38, 122
Polarized light, plane-, action of magnetic field on, 101
Polarization, of cell, 146, 147 ; of light, 135
Poles, 4, 6-9
Polonium, 173
Positive rays, 176
Potash, caustic, 50
Potassium, 50
Potential, 33, 122 ; in Maxwell's theory, 132
— difference, 78, 123 ; absolute measurement of, 117, 118
— gradient, 78
Priestley, Joseph, 27, 28, 30, 35, 37
Primary winding of induction instruments, 105, 106
Proton, 175-7
Prout's hypothesis, 170, 176
Quadrant electrometer, 117, 118
Quantity, electrostatic unit of, 115
Radioactivity, 173-4
Radium, 173
Rayleigh, Lord, 121
Refraction of light, 135
Resinous electricity, 21
Resistance, 33, 34, 78, 79, 80 ; specific, 78 ; absolute measurement of, 118-120 ; practical unit of, 121
—electrical, measurement of, 107-110
Resistance balance, 109, 110
Rheostat, Wheatstone's, 109
Röntgen, Wilhelm Conrad, 153, 165, 166, 167
Rotations, electro-magnetic, 85-7, 90 ; Arago's, 58, 90, 91, 93, 98, 99
Royal Institution, 46, 48, 155, 160
Royal Society, 130
Ruhmkorff, 104, 105
Rumford, Count, 17, 46
Rutherford, Sir E., 167, 171, 173, 174, 178
Saturn's rings, 130
Savart, 58
Schuster, 161, 162, 167
Schweigger, 74 ; his multiplier, 74, 91
Second, fundamental unit of time, 115
Secondary winding of induction instruments, 105, 106
Seebeck, Thomas Johann, 75
Self-induction, 96, 100, 133
's Gravesande, Wilhelm Jacob, 18, 19
Shakespeare, William, 1
Shell, magnetic, 71, 72
Siphon recorder, Kelvin's, 112
Soddy, Frederick, 174
Sodium, Davy's isolation of, 50
Solution pressure, Nernst's theory of, 151
South pole, *see* Poles

Specific inductive capacity, 33, 123, 134, 135, 143, 144
Specific resistance, 78
Stokes, Sir George, 171
Stoney, Johnstone, 160, 171
Sturgeon, William, 59
Tangent galvanometer, 71, 110, 116
Taylor, Richard, 115, 124
Telegraphy, 73, 108, 112, 114, 121 ; wireless, 105, 139, 140
Telephone, 106, 107, 147, 148
Temperature gradient, 77
Terellae, 6, 8, 11
Terrestrial magnetism, 111
Thermionic valve, 139, 175
Thermo-electric currents, 75
Thermopile, 75
Thompson, Benjamin, Count Rumford, 17, 46
Thomson, Sir J. J., 38, 162 ; on cathode rays, 163, 164, 167-73, 175 ; on positive rays, 176 ; on ionization of gases, 166, 167, 171, 172, 175
Thomson, William, *see* Kelvin, Lord
Thorium, 173
Torsion balance, 36, 37, 53
Transformer, 106
Two Fluid Theory, 21, 38, 53
Tyndall, 101
Ultra-violet light, 175
Units, absolute, 115-120, 121 ; electromagnetic, 115, 116, 123, 124 ; electrostatic, 115, 123, 124 ; fundamental and derived, 114, 115 ; practical, 120, 121
Uranium, 153, 173
Valve, thermionic, in wireless receiver, 139, 175
van't Hoff, 149-51
Variation, magnetic, 11, 12
Versoria, 6, 7, 8
Victoria, Queen, 102
Vinci, Leonardo da, 4
Vitreous electricity, 21
Volt, practical unit of electr
motive force, 121
Volta, Alessandro, 43-6, 55, 62
Voltaic battery, 43
— cell, theory of, 150, 151, 152
— pile, 43-6, 48-50, 54, 152
Vortices, Maxwell's molecular, 131
Watson, William, 23, 26, 28,
154, 155
Watt, 89
Wave theory, of light, 16, 32, 135
Waves, electro-magnetic, 136-4
178
Weber, Wilhelm, molecular theor
54, 72, 124, 125 ; absolu
measurement of resistance, 11
120 ; theory of induced cu
rents, 123 ; other reference
111, 114, 135
Wheatstone, Sir Charles, 108-11
114
Wheatstone's bridge, 110, 147, 148
William III, 12
Williamson, Alexander, 144, 145
Wilson, C. T. R., 171, 175
Wilson, H. A., 171
Wireless telegraphy, 105, 139, 14
Wireless loud-speaker, 107
Wollaston, William, 48, 76, 86, 88
X-ray spectra, 177, 178
X-rays, 105, 153, 165-7, 171, 17
174, 177, 178
Young, Thomas, 31

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of electr

55, 62

51, 152
52
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6, 28,

32, 13
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47, 1

, 145

39, 1

86, 8

71, 1

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